Exotics and BSM in ATLAS and CMS

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Outline

❖ Introduction

❖ Exotica searches

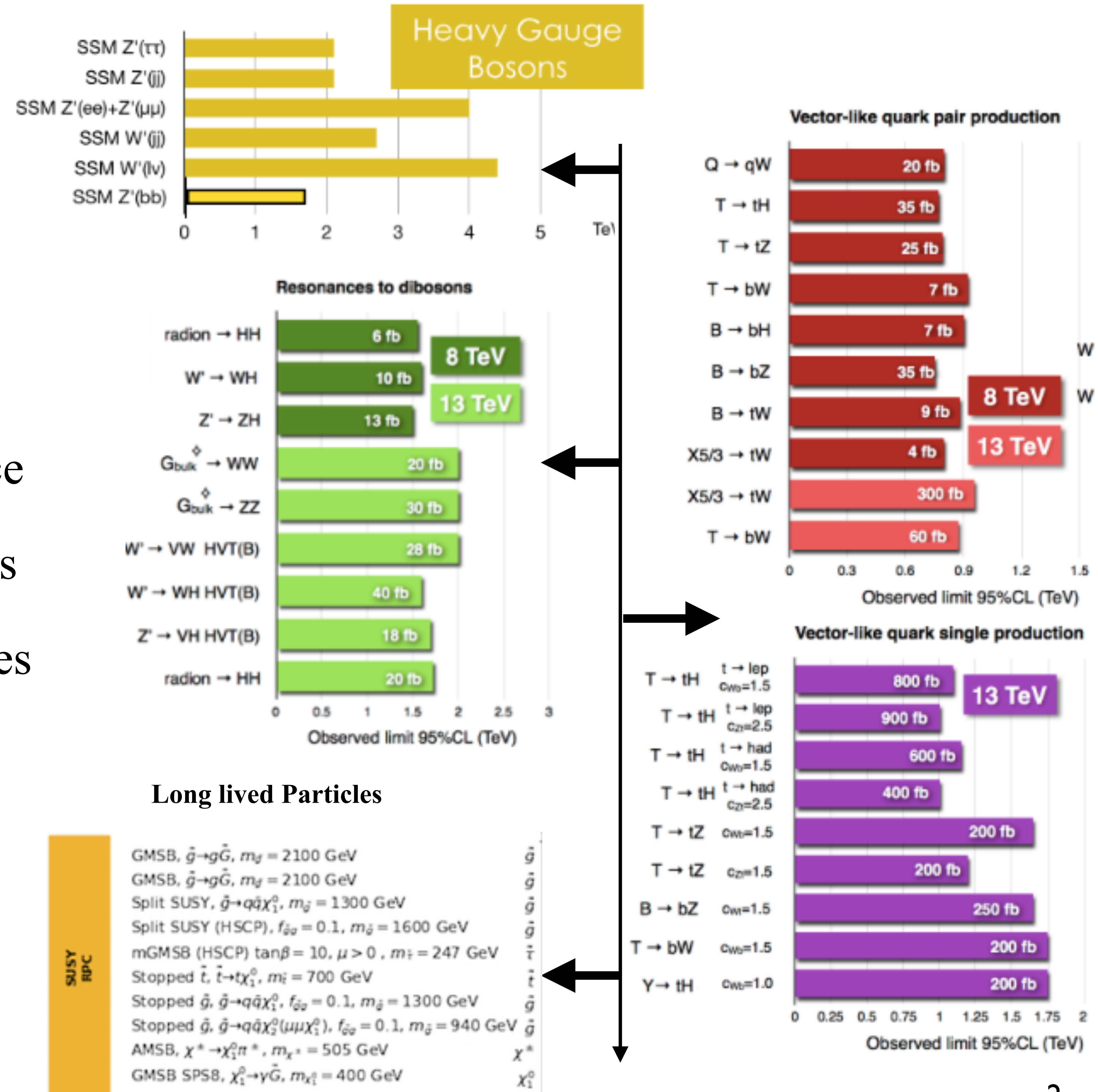
✦ Heavy Bosons

✦ Diboson Resonance

✦ Vector Like Quarks

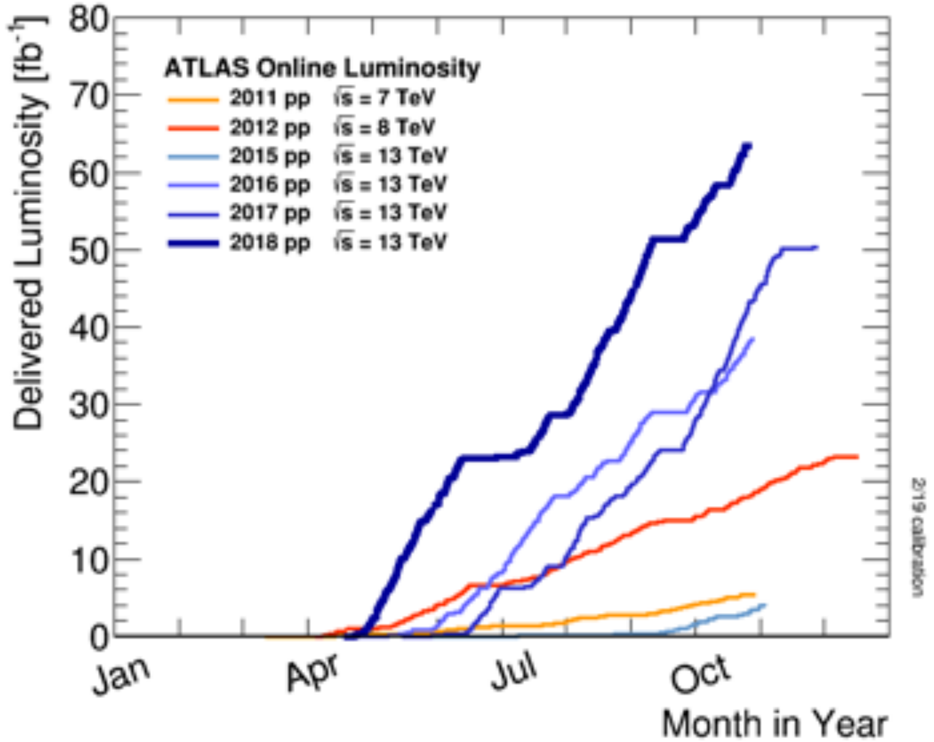
✦ Long-lived Particles

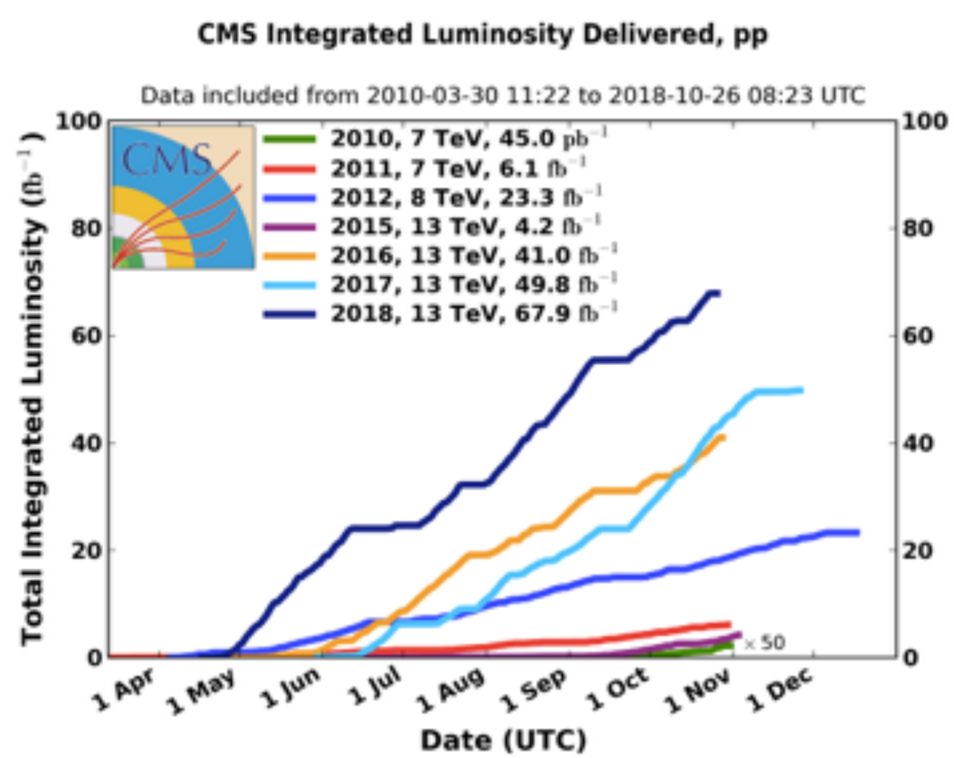
❖ Conclusion



Introduction

- **Discovery of a scalar boson consistent with SM Higgs**
  - Is it SM Higgs or something else ?
  - new window for physics beyond SM
- **Exotica searches**
  - cover wide range of final states
  - numerous models (extension of SM):
    - hierarchy problem
    - neutrino mass
    - dark matter
- **Successful Operation of LHC Run 2 (13TeV)**
  - both ATLAS and CMS: ~140fb^{-1} data for physics
  - Ideal place for exotica searches



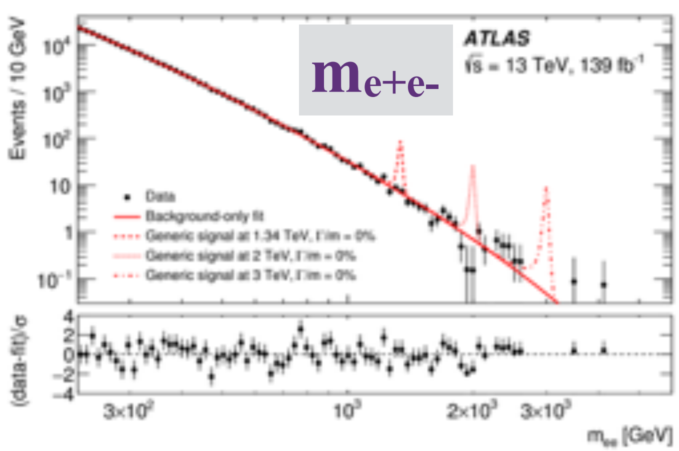


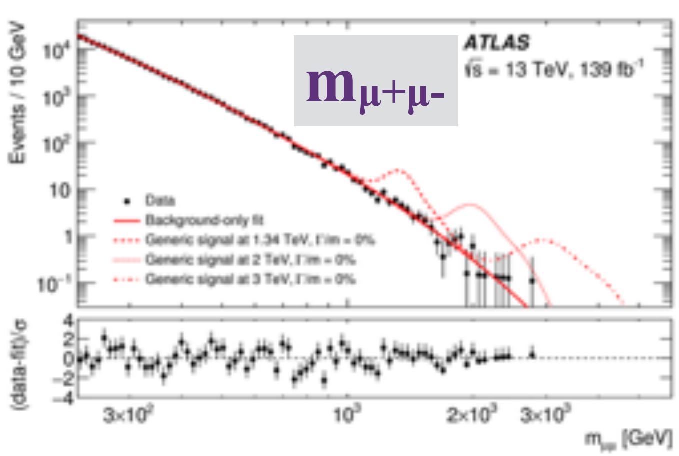
Heavy Boson Search

— Leptons final state

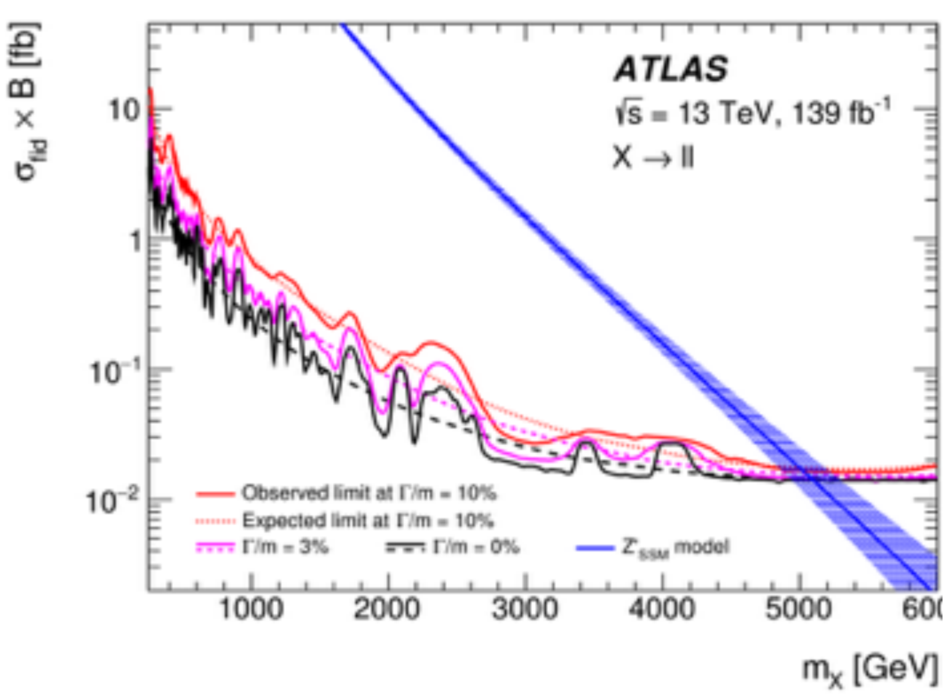
$Z' \to l^+l^-$

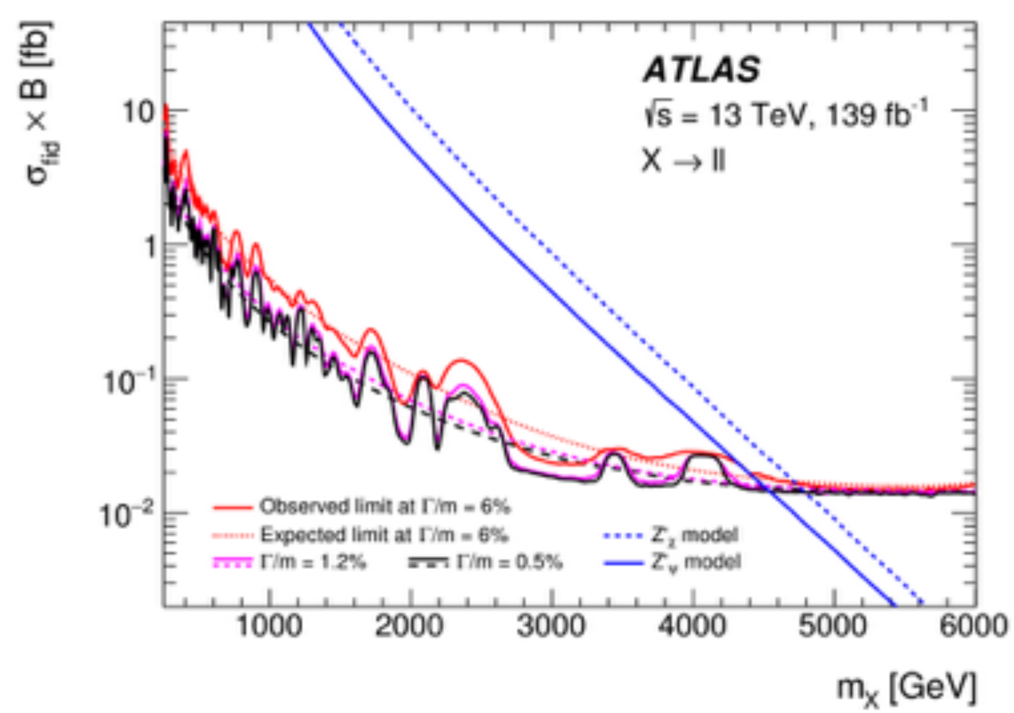
- **Generally, all new particles that can decay to dilepton called Z'**
- **Many BSM theories predict $Z' \to l^+l^-$**
  - **extension of SM in Grand Unification (e.g Z'_ψ)**
  - **some SUSY models predict new spin-0 resonance**
  - **sequential SM predict Z'_{SSM}**





Phys.Lett.B 796(2019)68





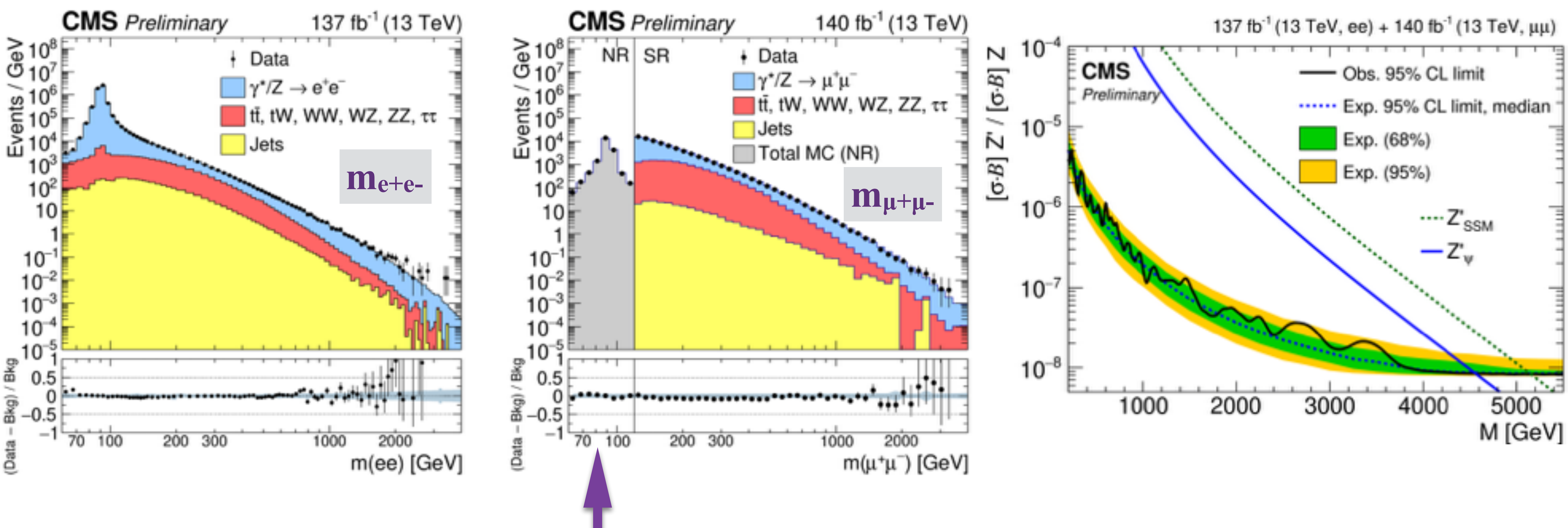
Good modelling for all data up to 3TeV.

Limit reach 5TeV for Z'_{SSM} and 4.5 TeV for Z'_ψ by all Run 2 data.

$Z' \to l^+l^-$

- Generally, all new particles that can decay to dilepton called Z'
- Many BSM theories predict $Z' \to l^+l^-$
    - extension of SM in Grand Unification (e.g Z'_ψ)
    - some SUSY models predict new spin-0 resonance
    - sequential SM predict Z'_{SSM}

CMS-PAS-EXO-19-019



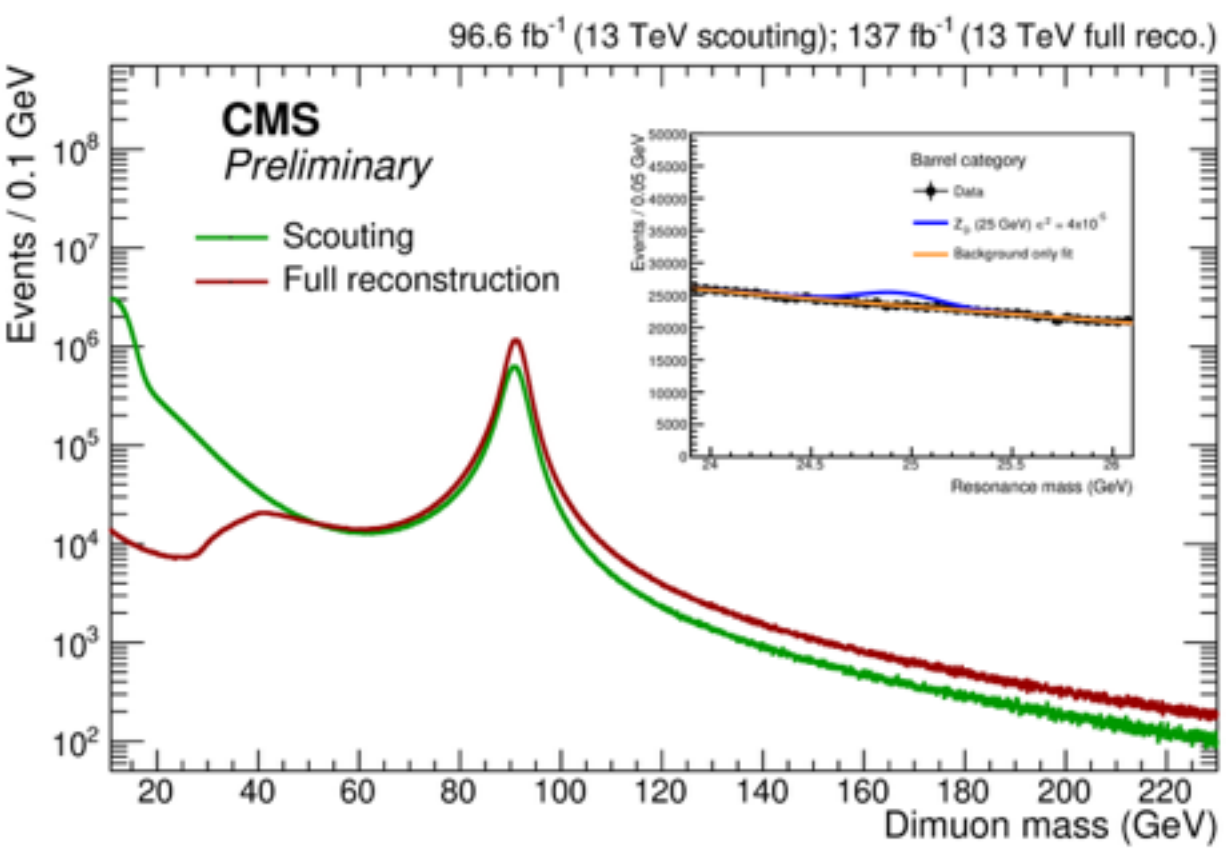
Prescaled muon trigger (27GeV) applied for $m_{\mu+\mu-}$ < 120GeV online.

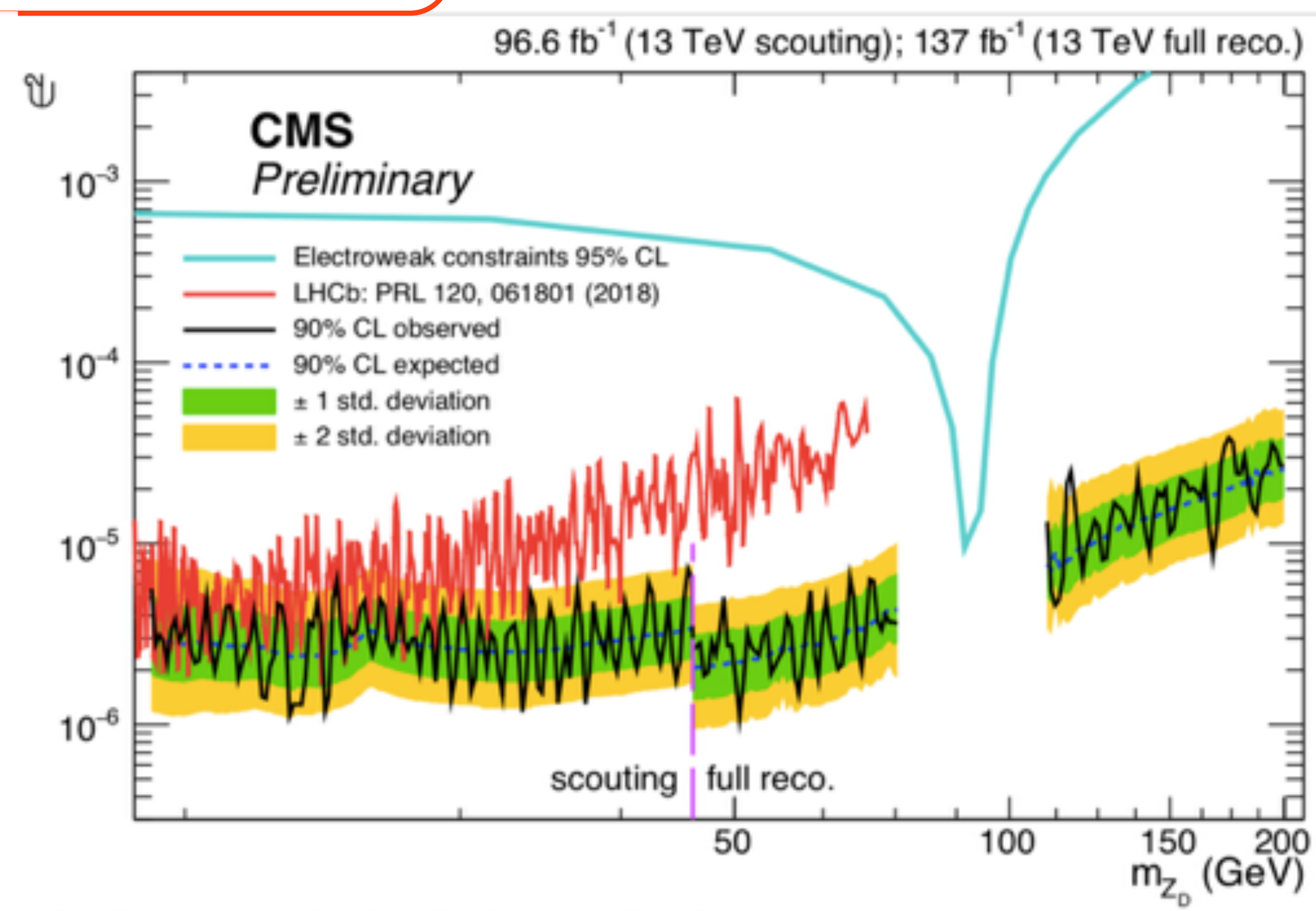
Limits similar as ATLAS: 5.15TeV for Z'_{SSM} and 4.56 TeV for Z'_ψ

di-muon low mass

- Search for resonance in $m_{\mu^+\mu^-}$ range of [45, 75] & [110, 200] GeV with full reco data (139 fb^{-1})
    - p_T > 20(10) GeV for 2 OS muons
- Search for bumps in $m_{\mu^+\mu^-}$ range of [11.5, 45] GeV with scouting data (~ 100 fb^{-1})
    - reduced trigger information, only muon related data is partially recorded.
    - offline muon p_T > 4 GeV

CMS-PAS-EXO-19-018



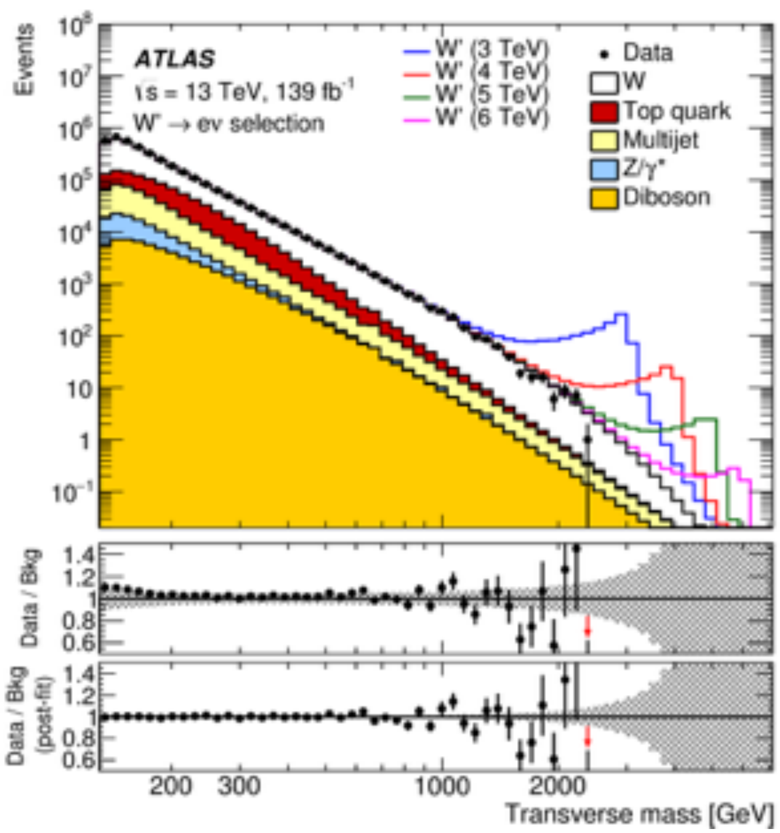


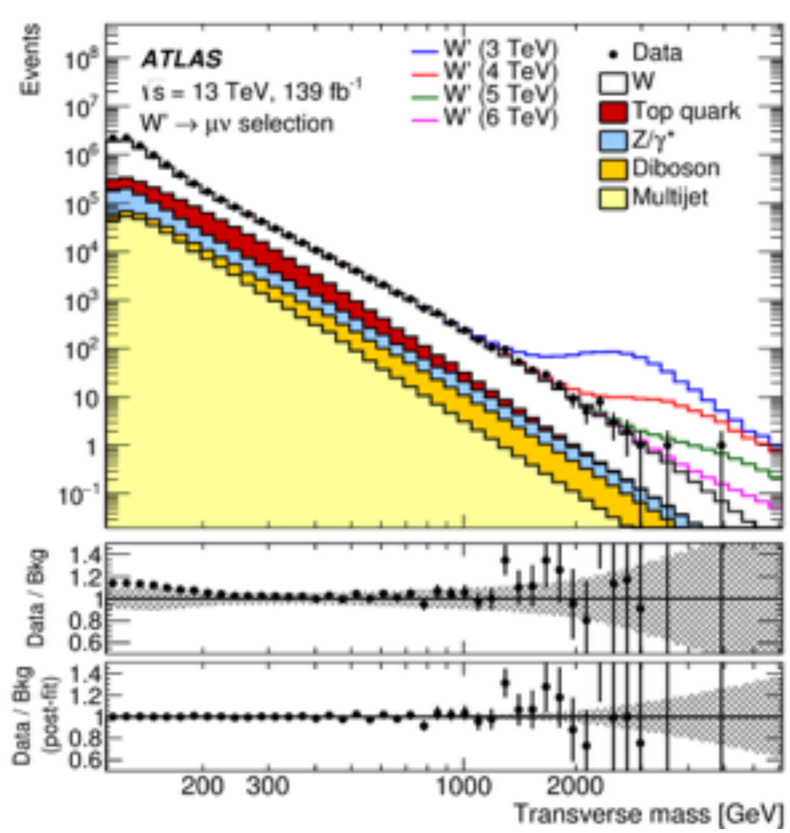
The most stringent limits for dark photon in the low $m_{\mu^+\mu^-}$ region.

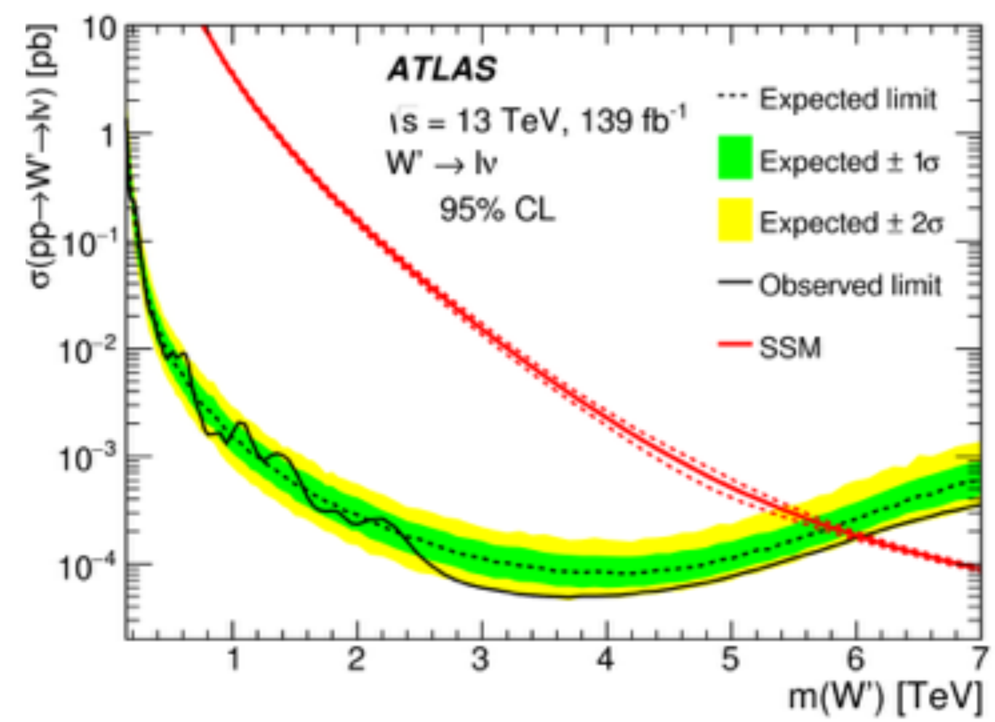
W'→lv

- **Search for heavy boson with lepton+MET signature.**
- **Look for excess on the transverse mass distribution.**
- **Dominant backgrounds coming from: W+jets, Top, QCD, Z, multi-bosons**

arXiv: 1906.05609







Assuming W' boson with the same coupling as the SM W boson, W' masses below 6 TeV are excluded at 95% CL in SSM.

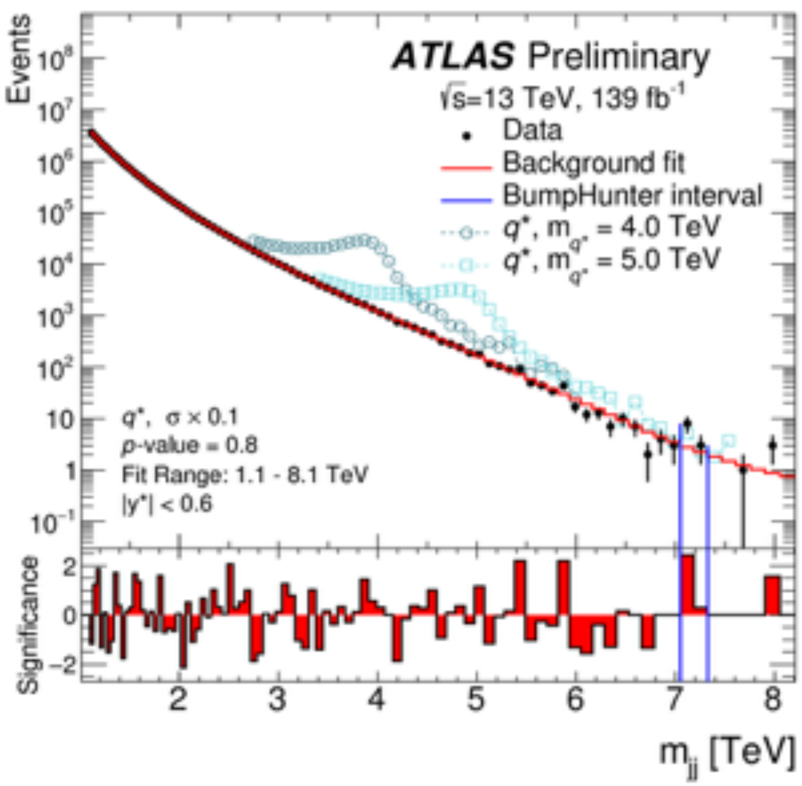
Heavy Boson Search

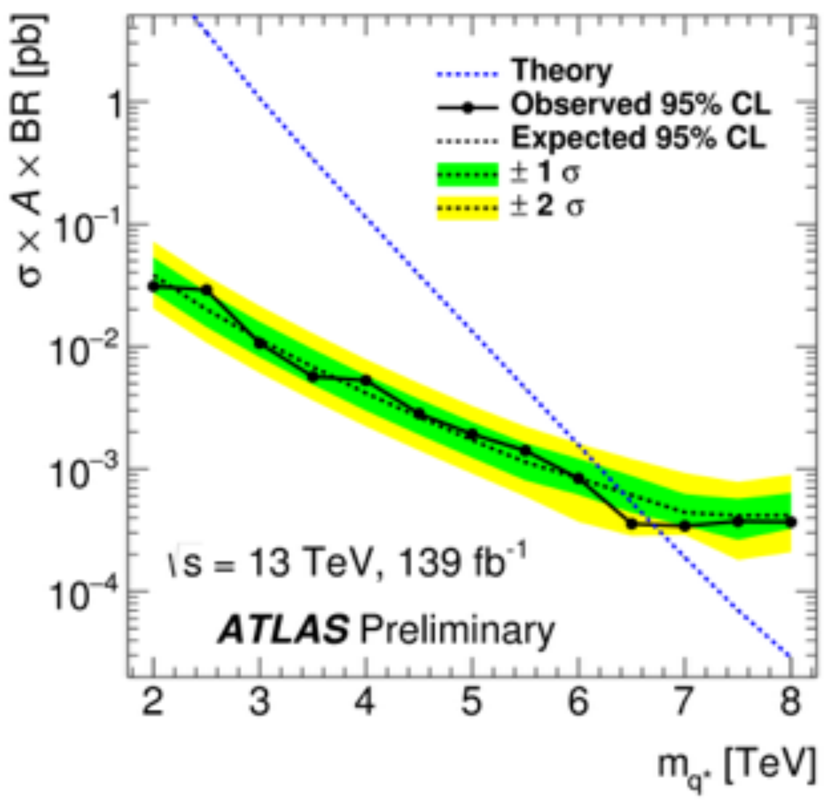
— Dijet final State

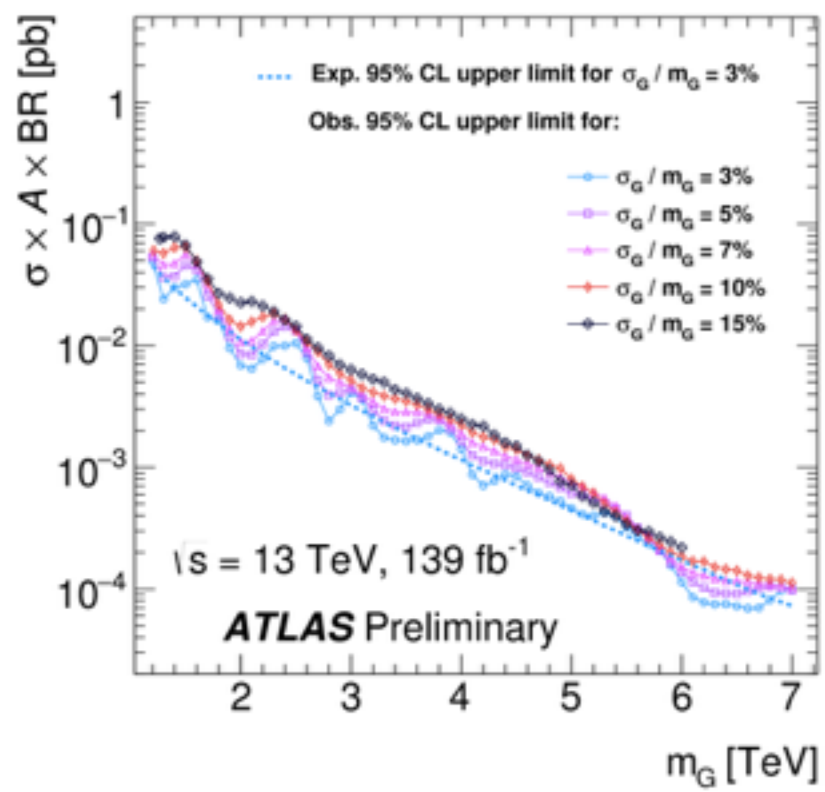
Di-jet resonance

- Probe numerous BSM models: String, Axigluons/Colorons, Color-octet scalar, W'/Z' bosons, RS …
- Search for bumps on the smoothly falling di-jet invariant mass spectrum.

ATLAS-CONF-2019-007







Also look for Gaussian shaped signal with different Relative Width Hypothesis.

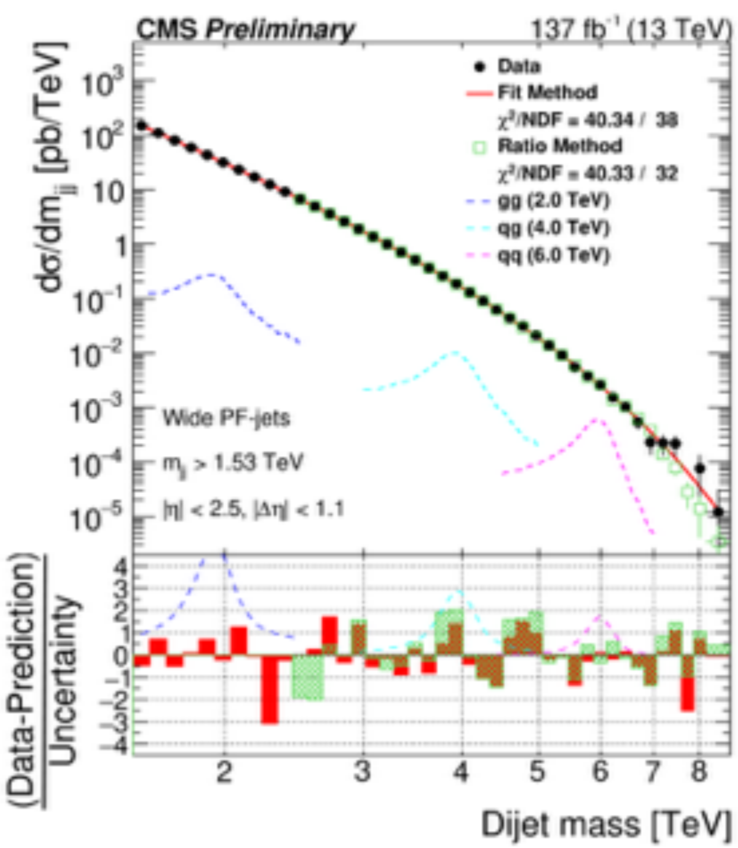
No significant excess observed.

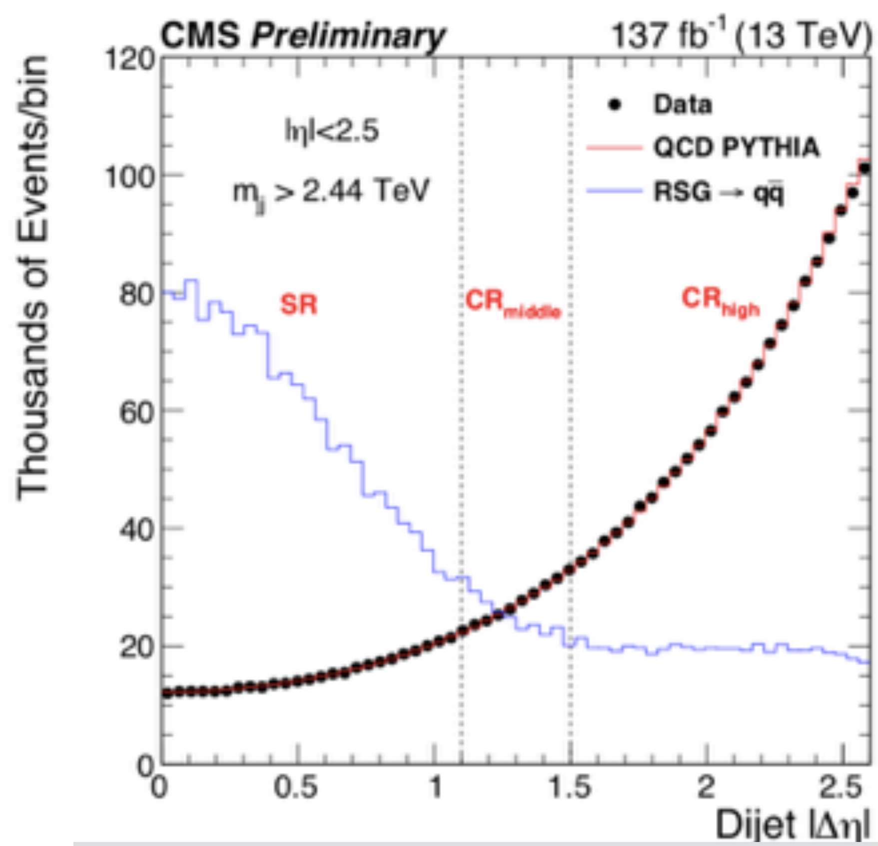
Mass limit of q* up to 6.7 TeV with full Run 2 data.

Di-jet resonance

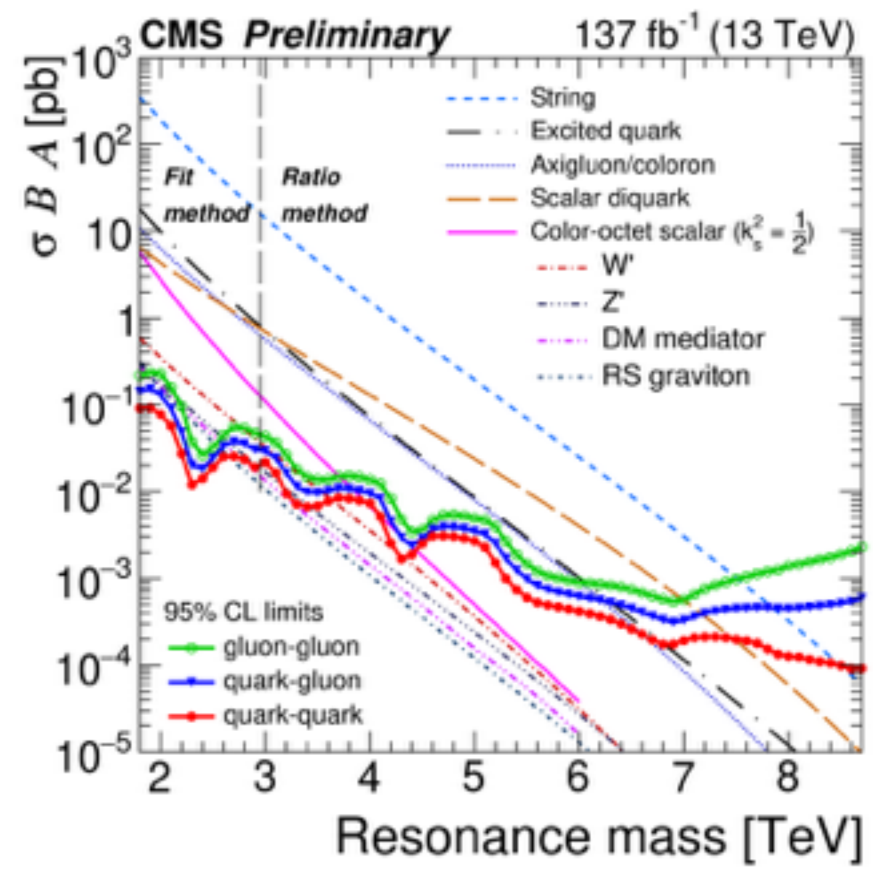
- Probe numerous BSM models: String, Axigluons/Colorons, Color-octet scalar, W'/Z' bosons, RS …
- Search for bumps on the smoothly falling di-jet invariant mass spectrum.

CMS-PAS-EXO-19-012





Introduce two CRs to constrain the bkg.
Big improvement w.r.t fit method in SR alone.



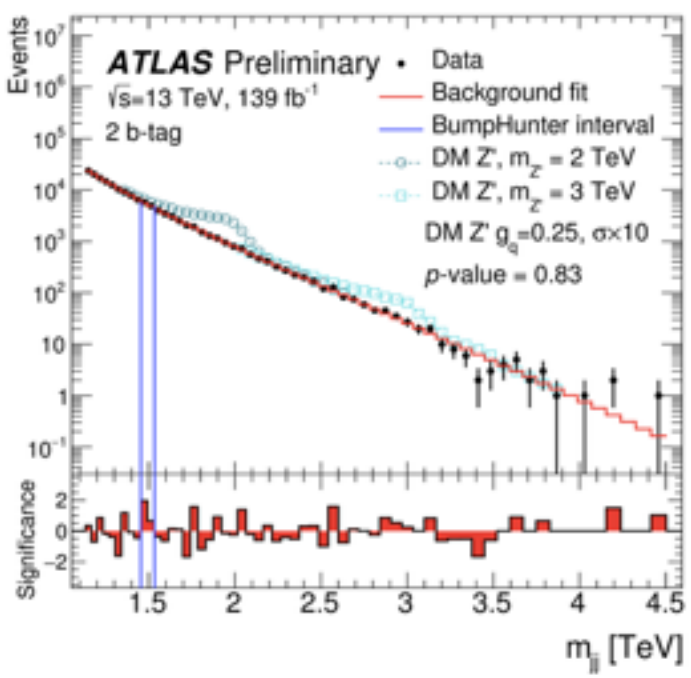
Excellent modelling of data!

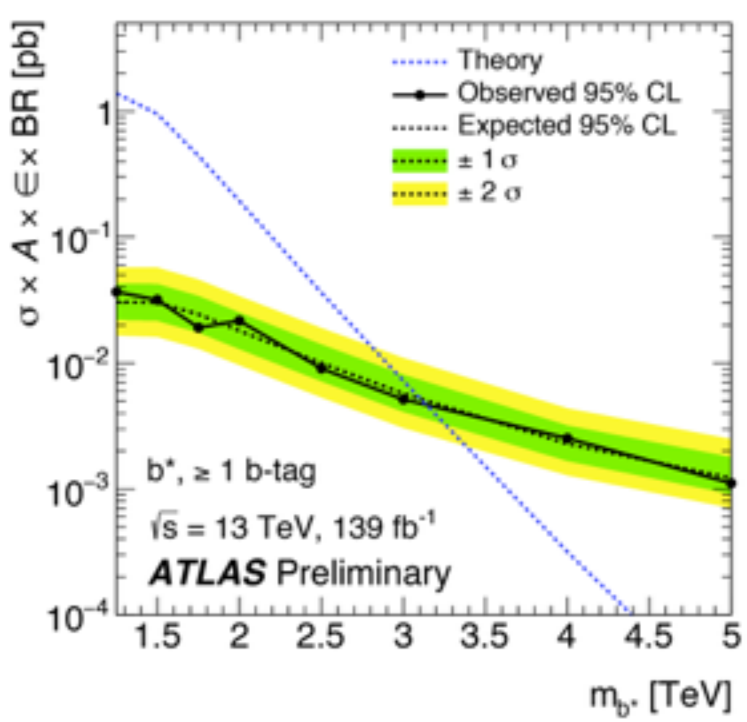
Mass limits up to 7.9 TeV for different models.

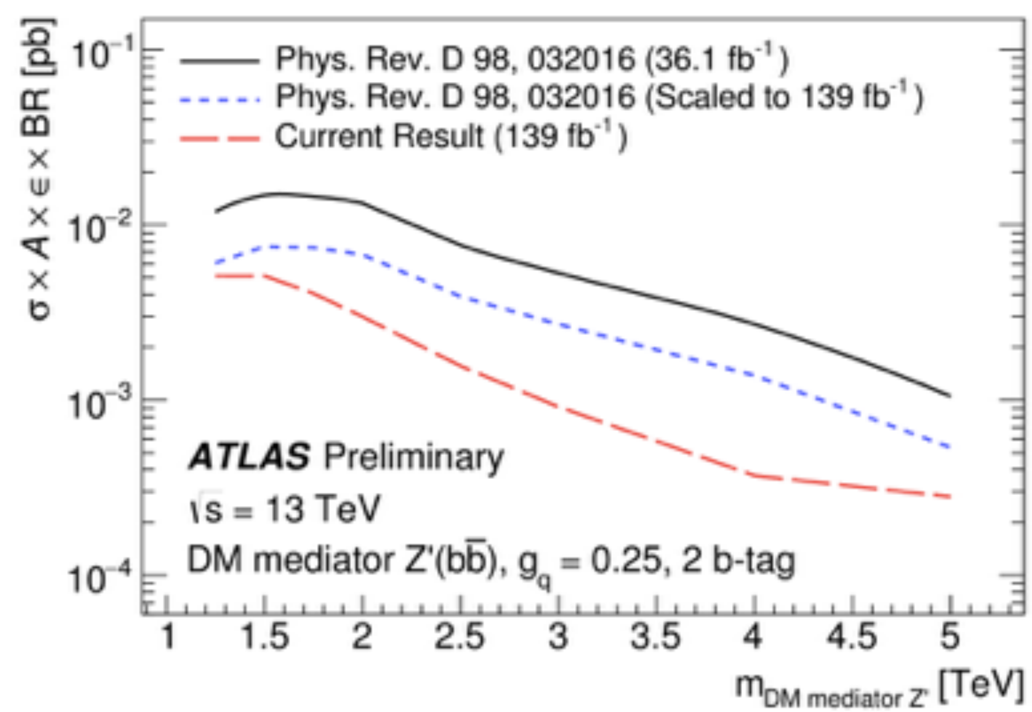
Di-bjet Resonance

- Test on BSM models: b*, DM Z'(bb), KK G(bb), SSM Z'(bb)
- Use b-tagging, categories based on the # of b-tagged jets: ≥ 1 b-tag, 2 b-tags
- First use new Deep Learning for B-tagging algorithm
  - Significantly improve the sensitivity (a factor of 1~3.7)

EXOT-2019-03







Good agreement between Data/MC(bkg only).

Limit moves up to 3.2 TeV for b*.

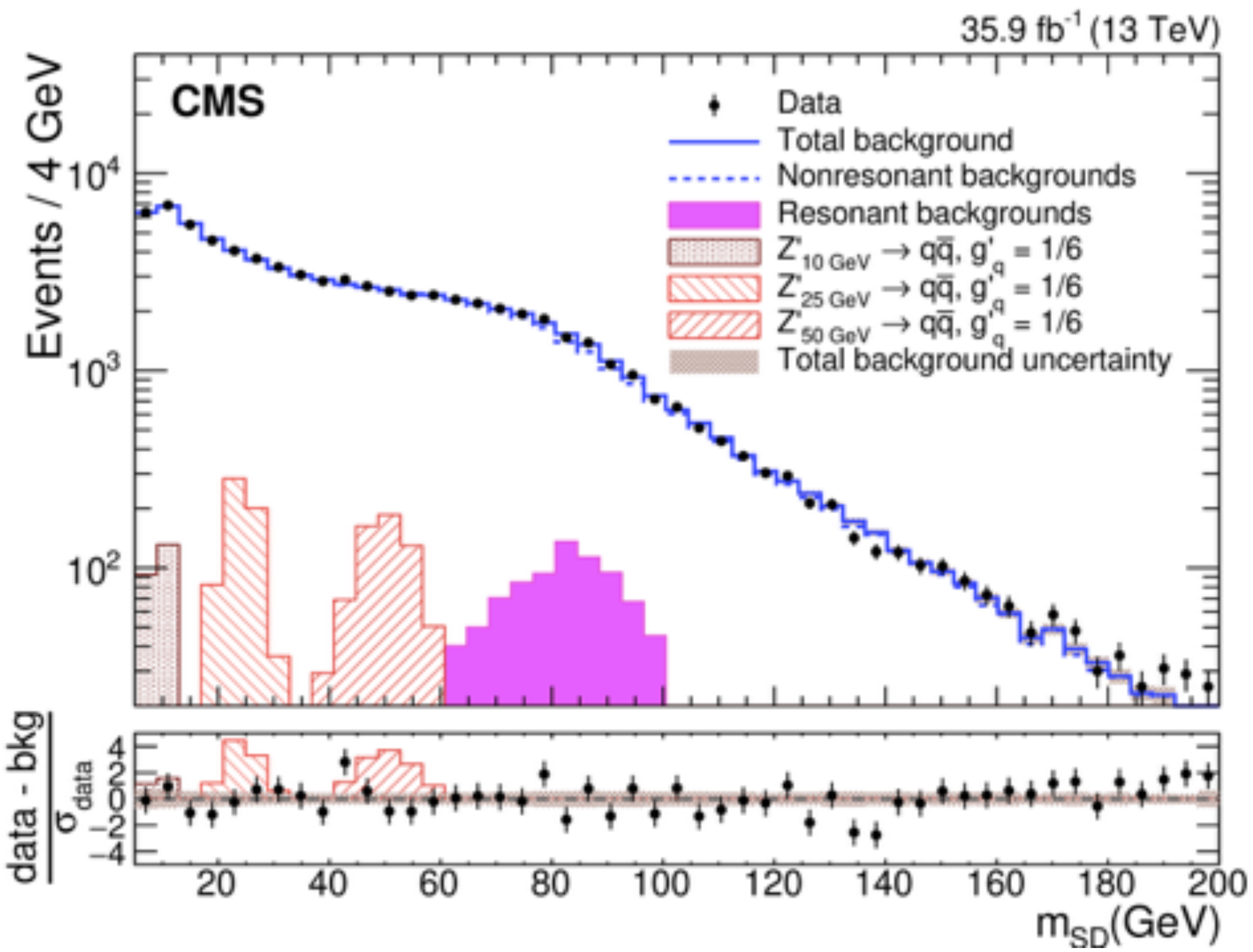
		observed	expected
1b	b^*	3.2 TeV	3.1 TeV
2b	DM mediator Z' $g_q = 0.20$	2.8 TeV	2.8 TeV
	DM mediator Z', $g_q = 0.25$	2.9 TeV	3.0 TeV
	SSM Z',	2.7 TeV	2.7 TeV
	graviton, $k/\overline{M}_{PL} = 0.2$	2.8 TeV	2.9 TeV

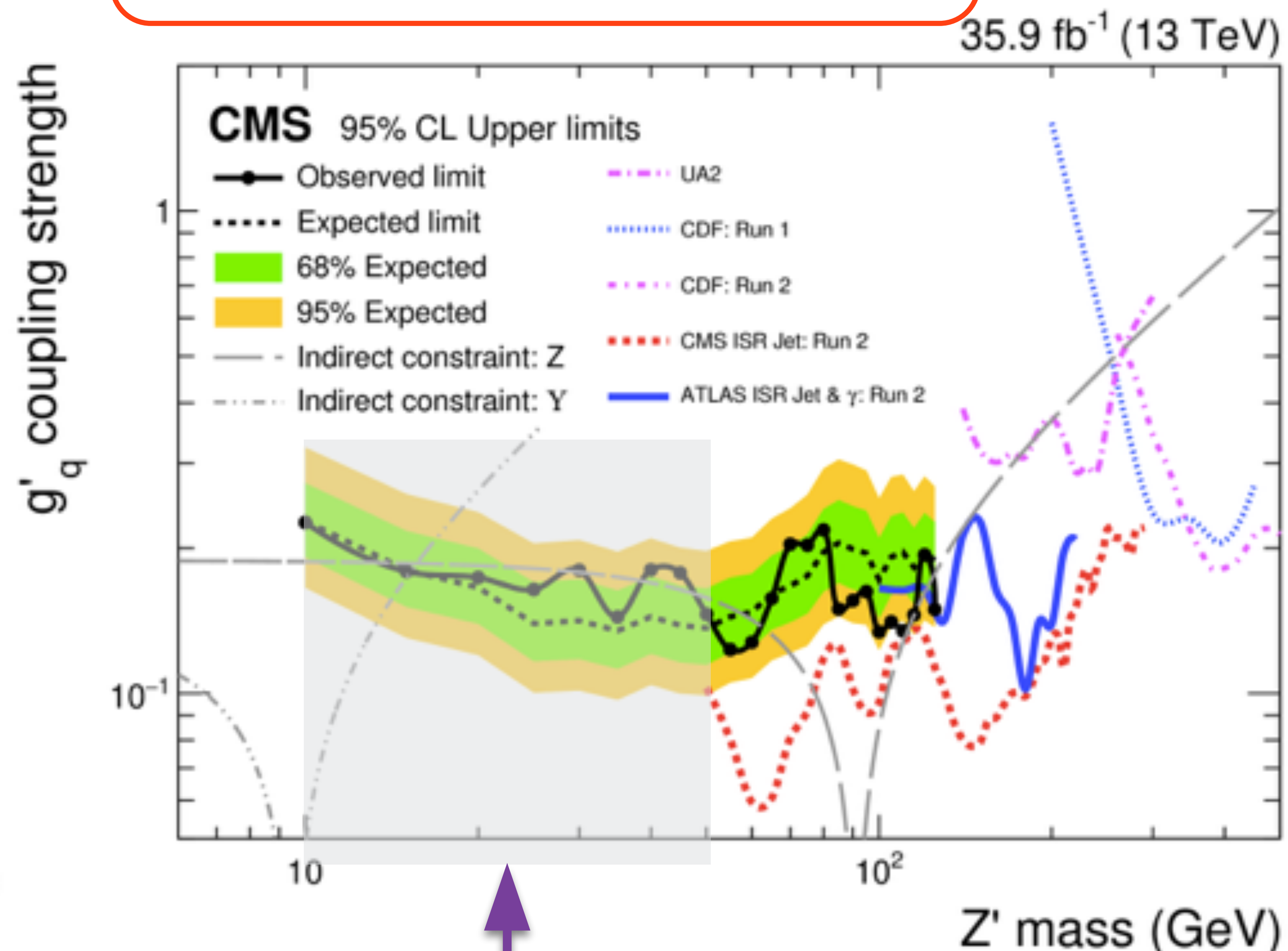
Low Mass Dijet Resonance

- High Mass: ~1.5 - 8 TeV — Standard trigger (jet trigger or Large H_T)
- Medium Mass: ~ 0.4 - 2 TeV — Dedicated b-trigger or jet trigger
- Low Mass: ~0.2 - 1 TeV — Dijet + ISR (trigger!)
- Very Low Mass: ~ 10 - 200 GeV — Boosted Dijet + ISR (trigger!)

Boosted Dijet + ISR photon

arXiv:1905.10331



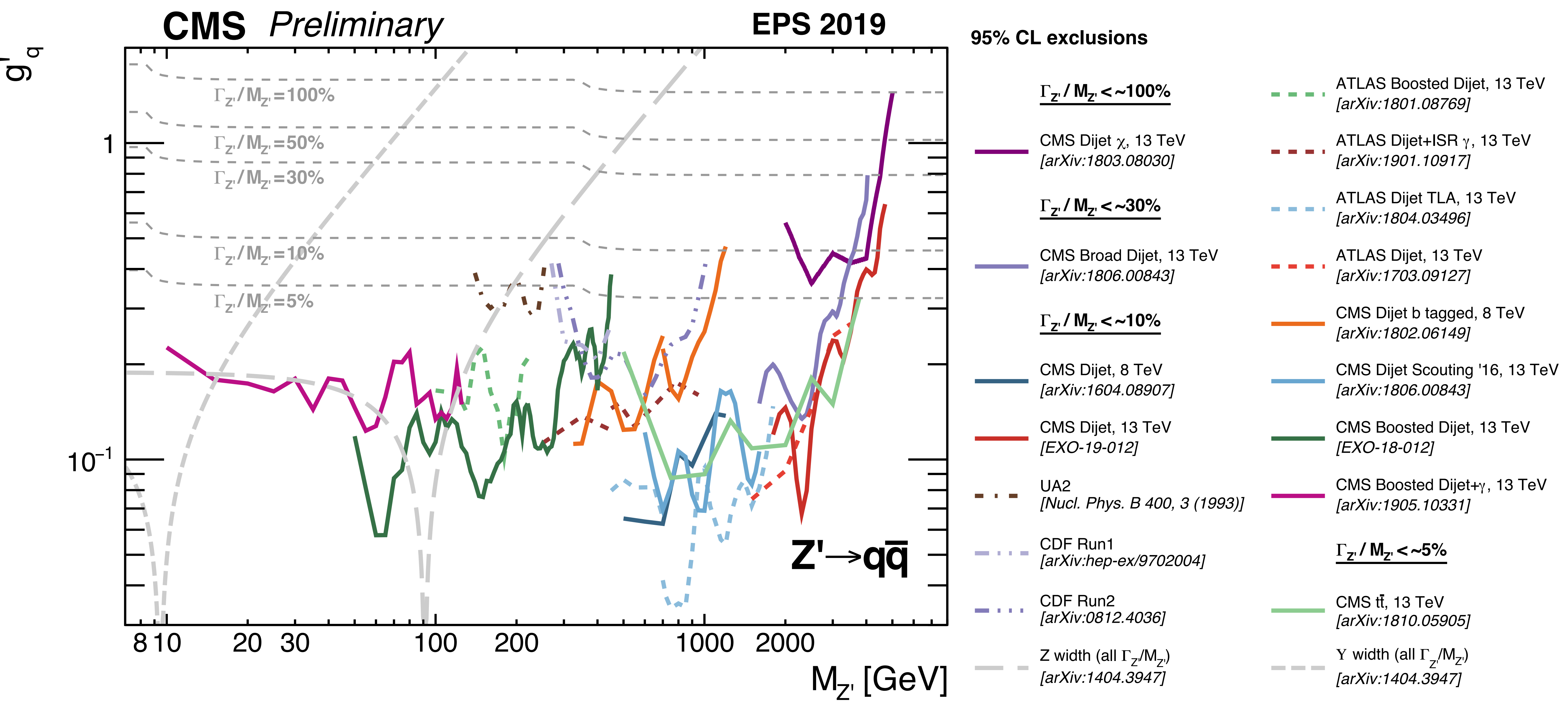


Resonant bkg normalised from CR.

Non-Resonant bkg estimated from fit.

First limits for dijet mass < 50 GeV with direct search in LHC.

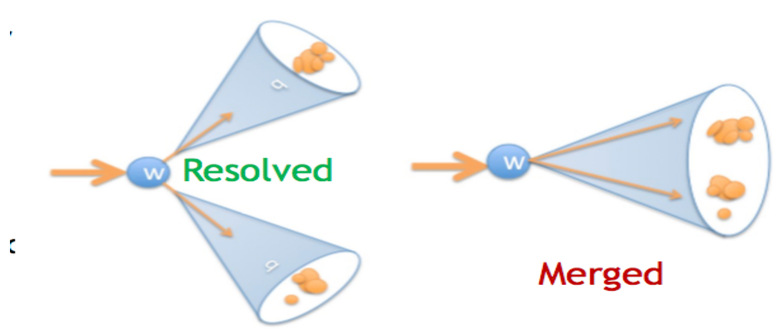
di-jet Resonance Summary plot

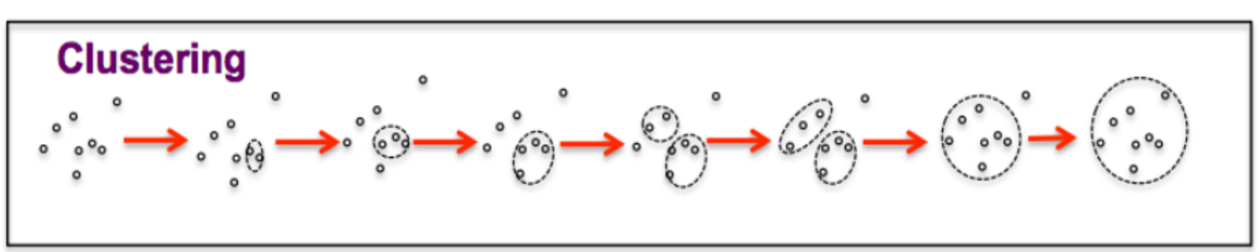


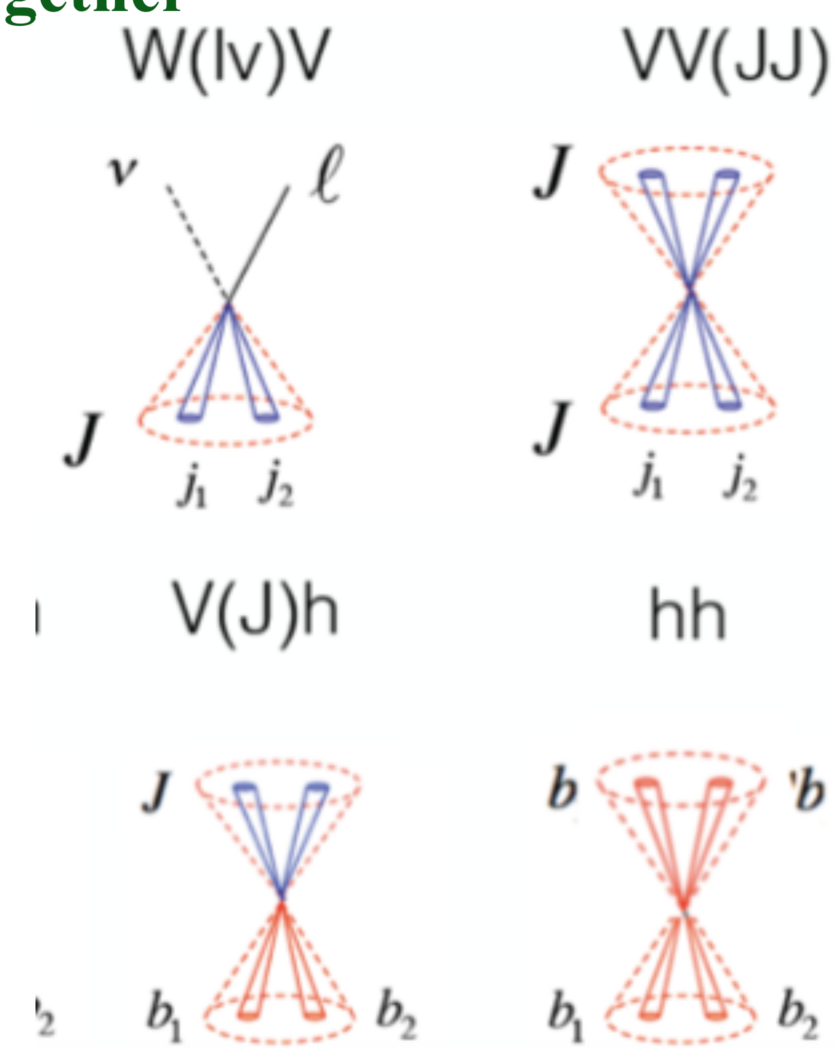
Diboson Resonance

- Rich program of diboson resonance search
  - Spin 0: S/H → WW/ZZ: extended Higgs sectors, scalar singlet
  - Spin 1: V' → VH/VV: Heavy Vector Triplet
  - Spin 2: G* → VV: Extra dimensions
- Unable to cover all the final states in this talk. Only select a recent analysis.

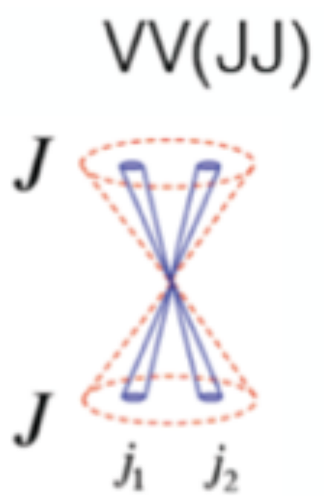
- Highly boosted W/Z/H decay products are merged together
- Use jet sub-structure algorithm to tag boosted object





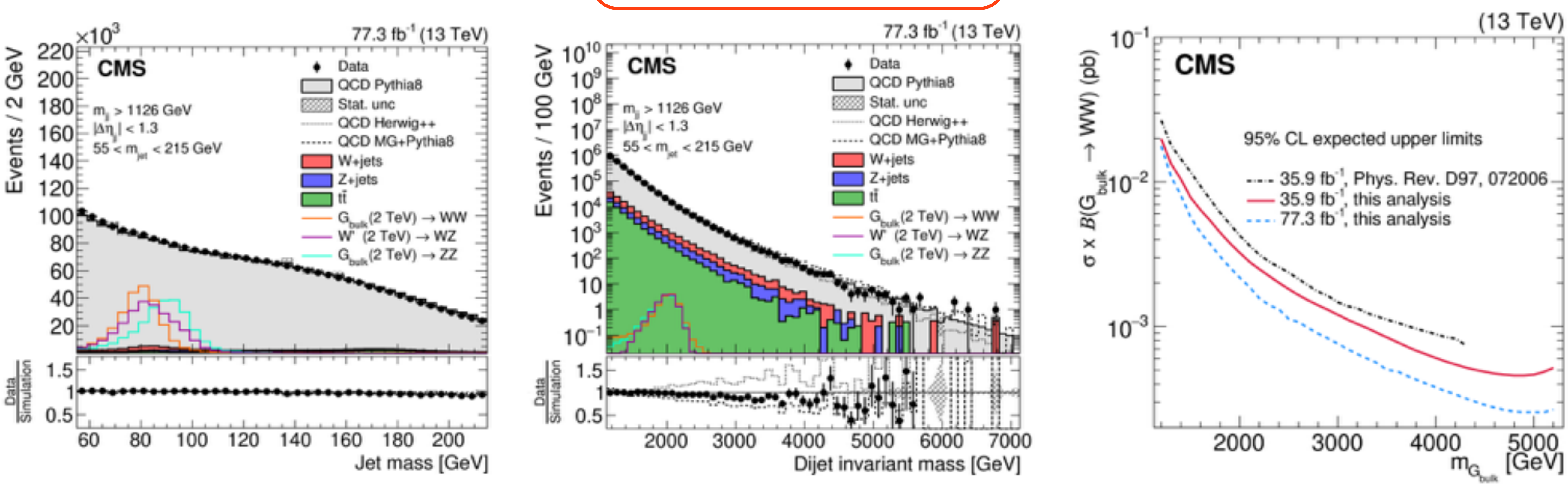


"Dijet" —— WW/WZ/ZZ Fully Hadronic decay



- **Focus on the potential resonances with mass above 1.2 TeV, W/Z boson expected to be collimated into a fat jet**
- **Novel method: three-dimensional maximum likelihood fit of two jets masses and the dijet invariant mass: improve sensitivity by ~30% w.r.t previous methods.**

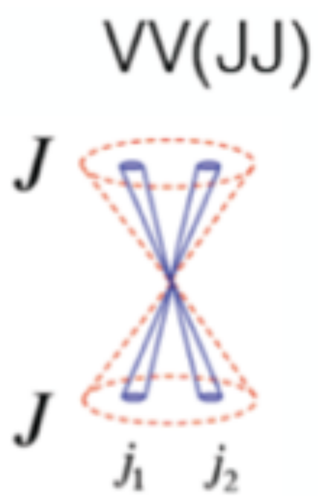
CMS-PAS-B2G-18-002



No excess above the standard model background!

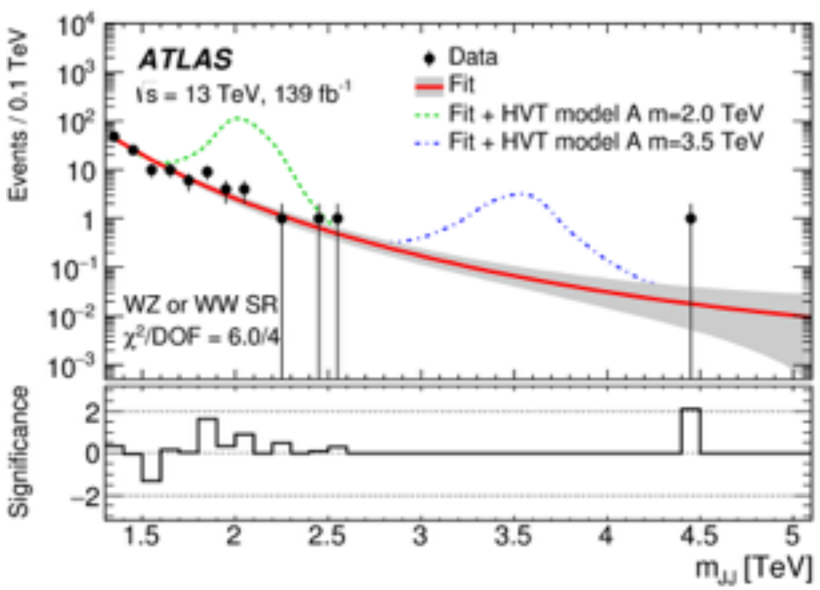
Exclude spin-1 W' and Z' with masses lower than 3.8 TeV and 3.5TeV respectively.

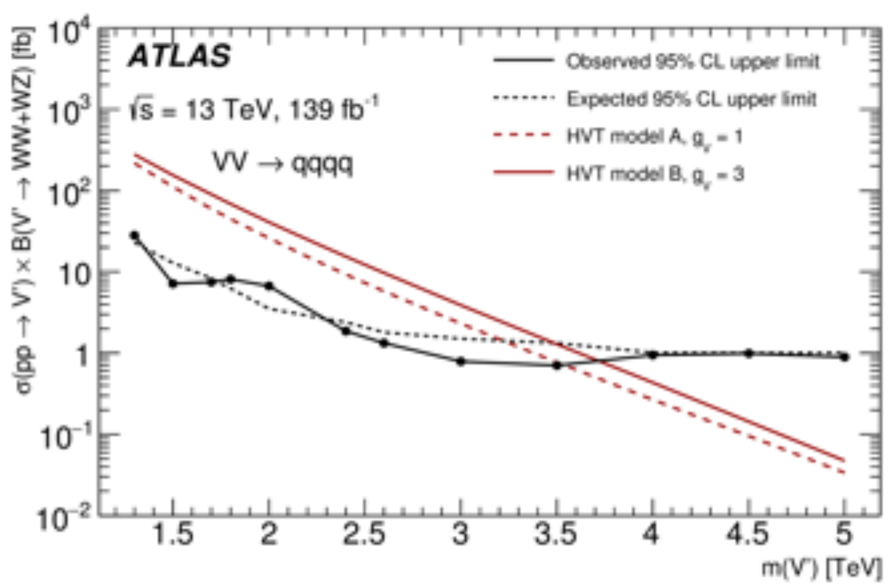
“Dijet” —— WW/WZ/ZZ Fully Hadronic decay

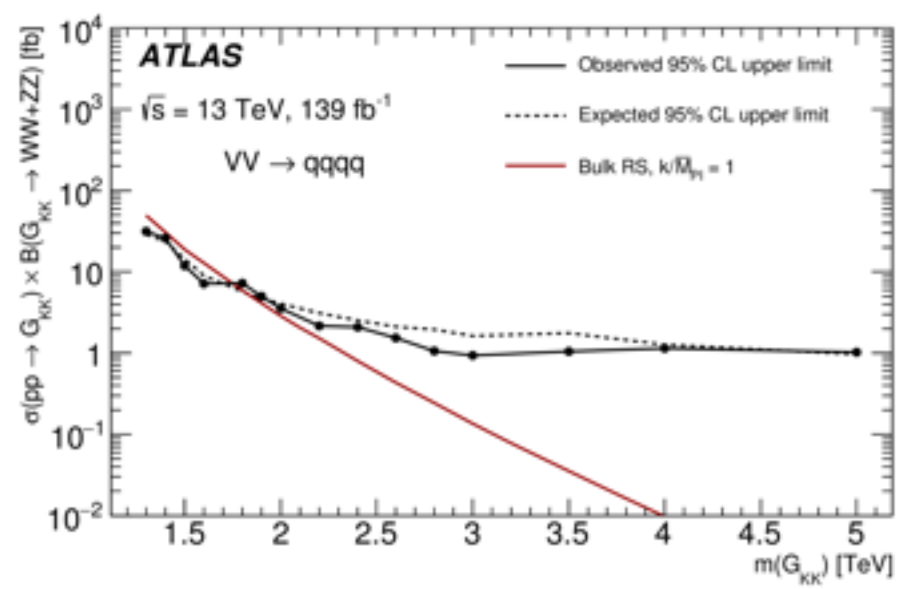


- Similar analysis performed in ATLAS using the **Full Run 2 data**
- Several improvements w.r.t Run 1 or 2016 analysis:
  - include track info in the Calorimeter based jets
  - include Jet mass and more powerful Jet substructure variables in the boosted boson finding

arXiv:1906.08589







No obvious hint of bump above the falling SM background!

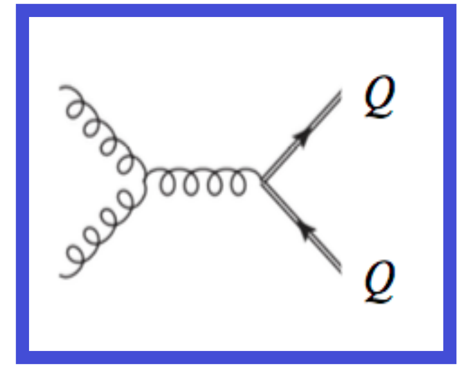
Exclude HVT W’/Z’ with masses up to 3.8 TeV.

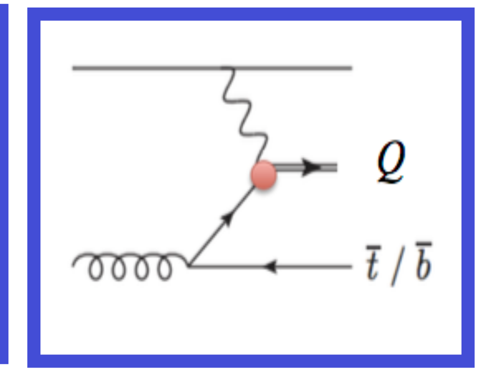
Exclude Bulk RS Graviton with masses up to 1.8 TeV.

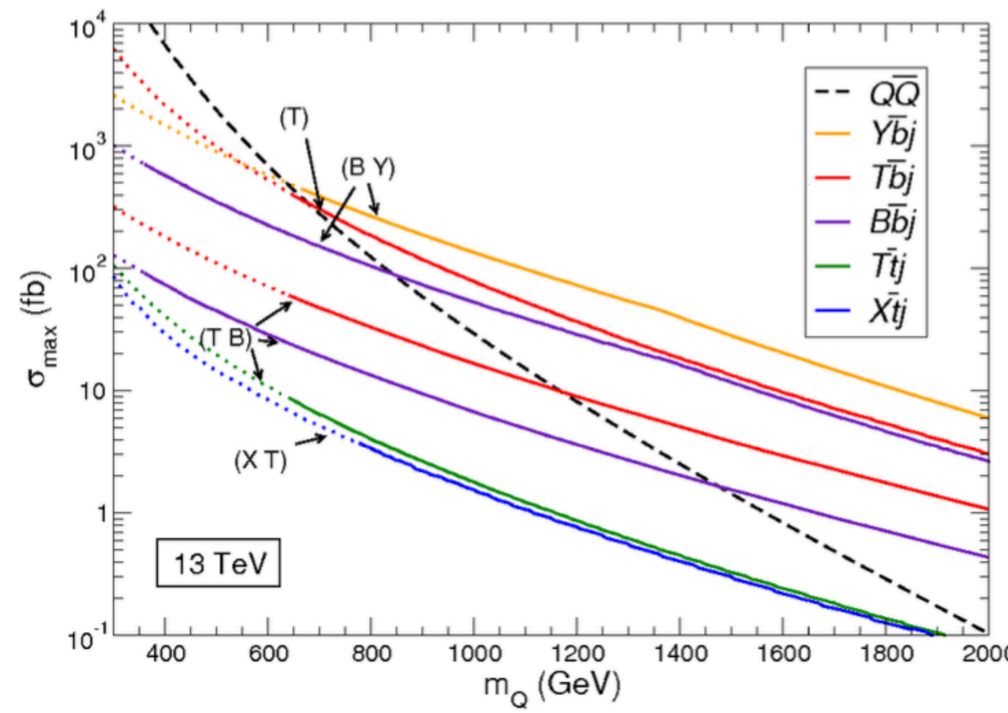
Vector-Like Quarks Search

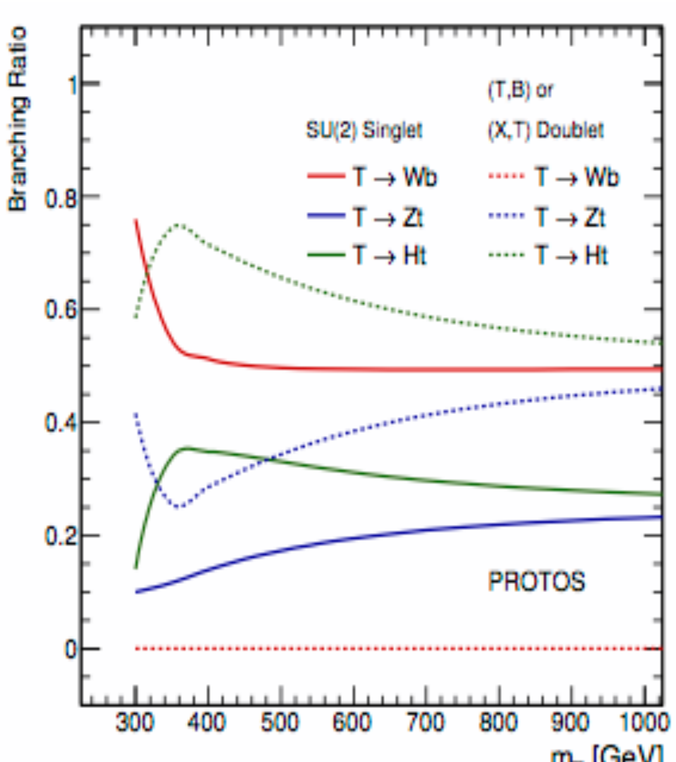
Vector-Like Quarks

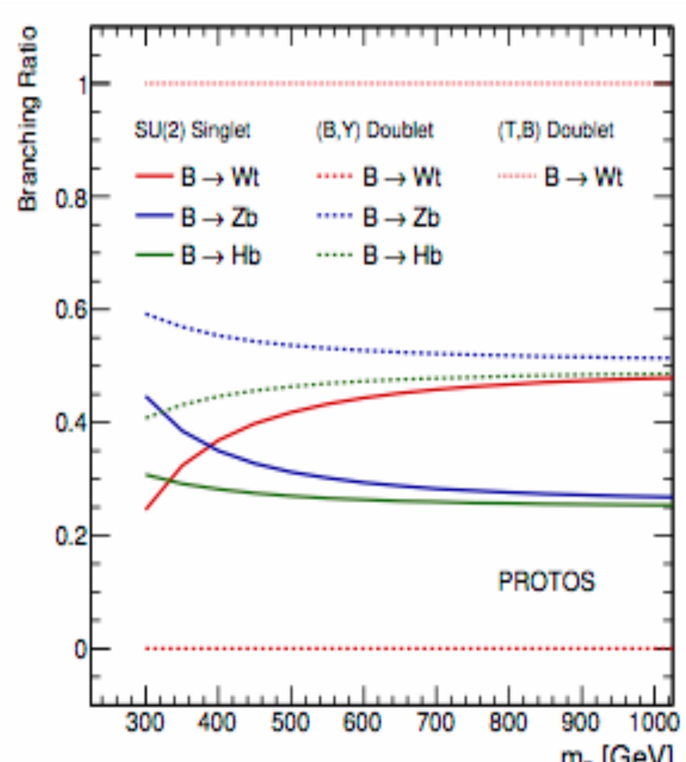
- Extra family of spin 1/2 quarks
  - symmetric vector-like coupling to W/Z
  - Mass from direct mass term
  - Can solve hierarchy problem
- Pair production from strong interaction
  - Model independent
- Single production from electroweak
  - Depends mixing with SM quarks
- Decays to boson+heavy quark

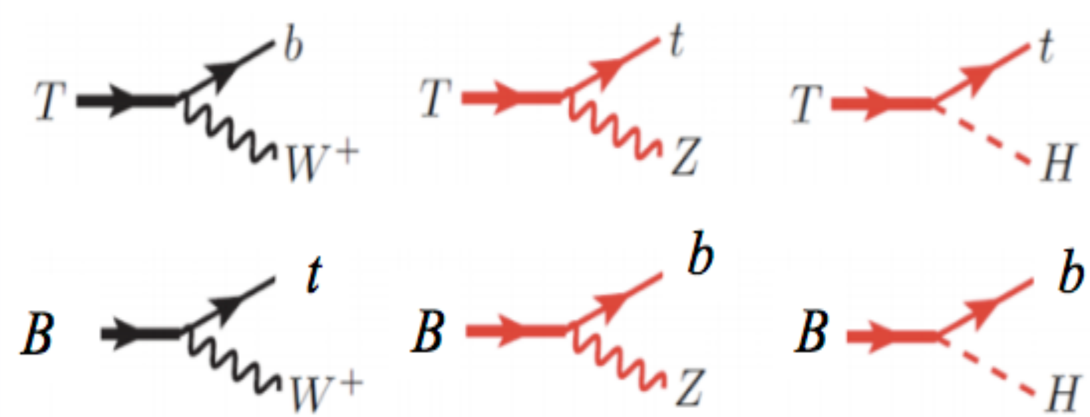






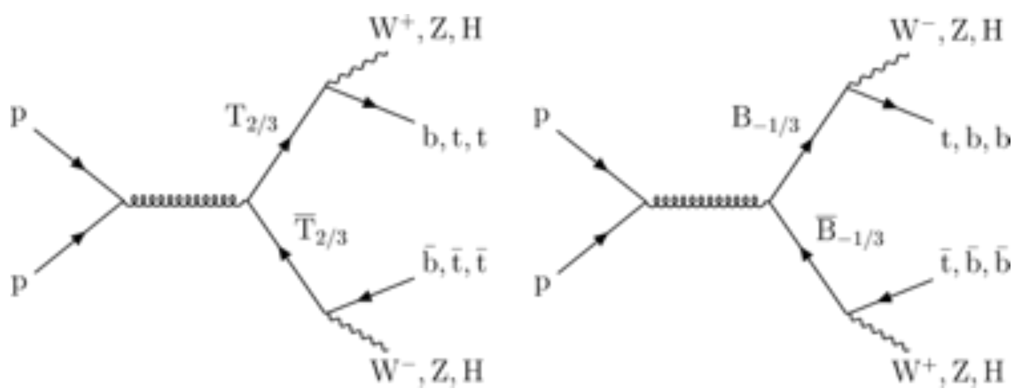


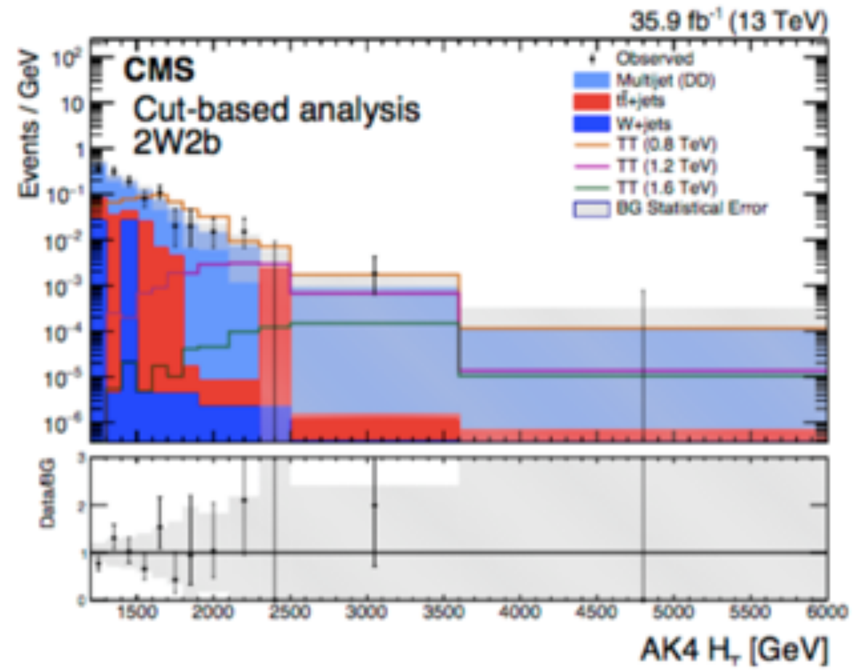


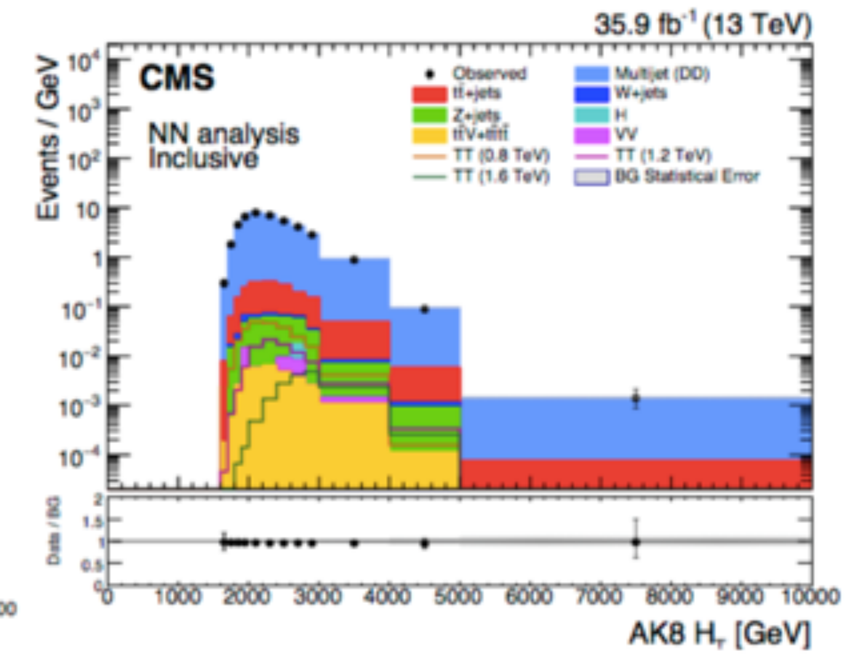


Pair-Produced VLQ

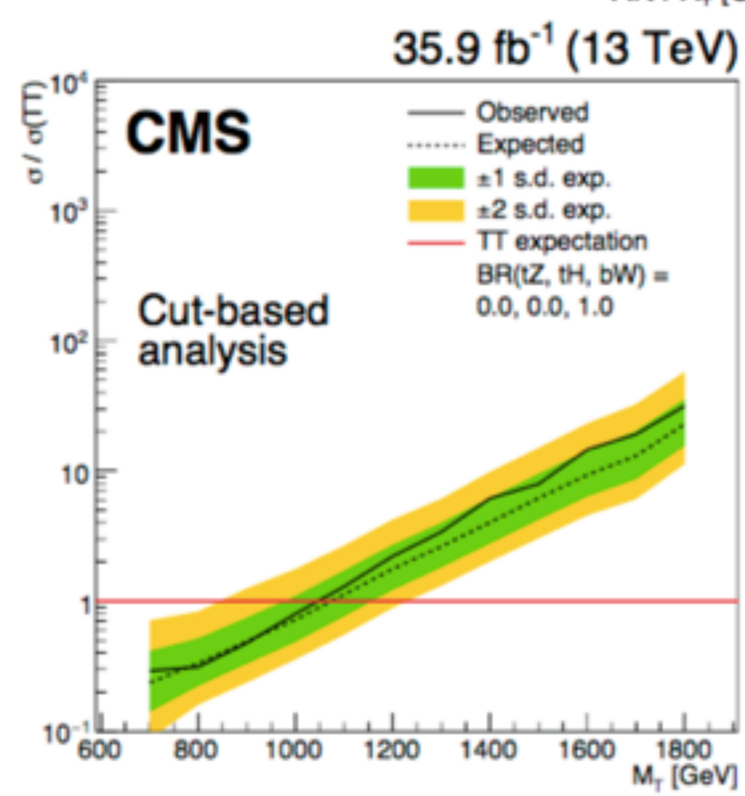
CMS-PAS-B2G-18-005

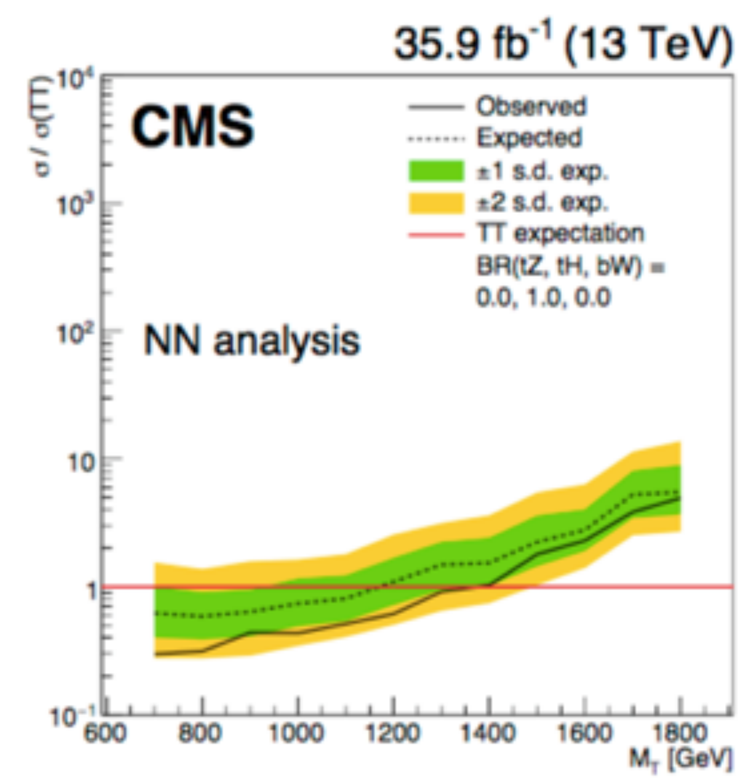






- **Fully hadronic final states:**
  - **requiring ≥4 jets**
- **Two independent searches:**
  - **cut-based: TT→WbWb**
  - **Neural-Network: boosted event shape tagger algorithm to identify jets from t, b, W, Z or H, account all TT, BB hadronic final states.**

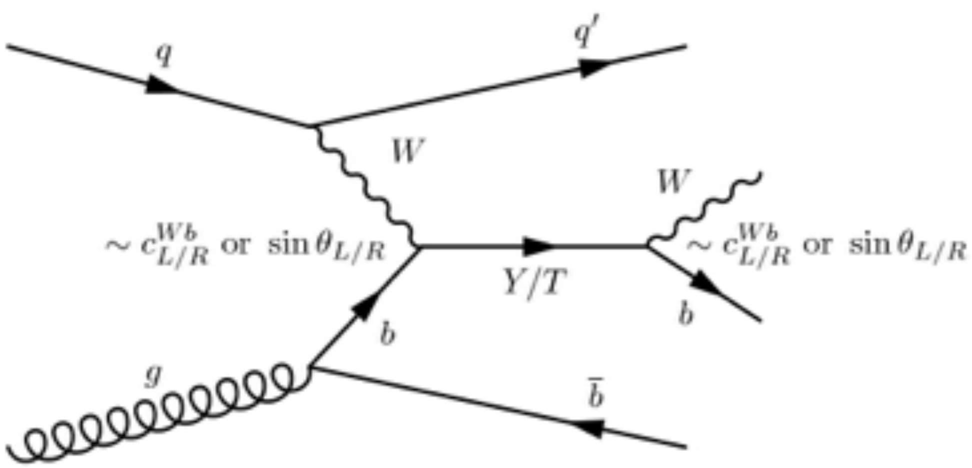




Limit for M_T at 1040 GeV if BR(T→Wb) =1

Limit for M_T at 1370 GeV if BR(T→tH) =1

Singly Produced VLQ



$$Y/T \rightarrow Wb \rightarrow l\nu b$$

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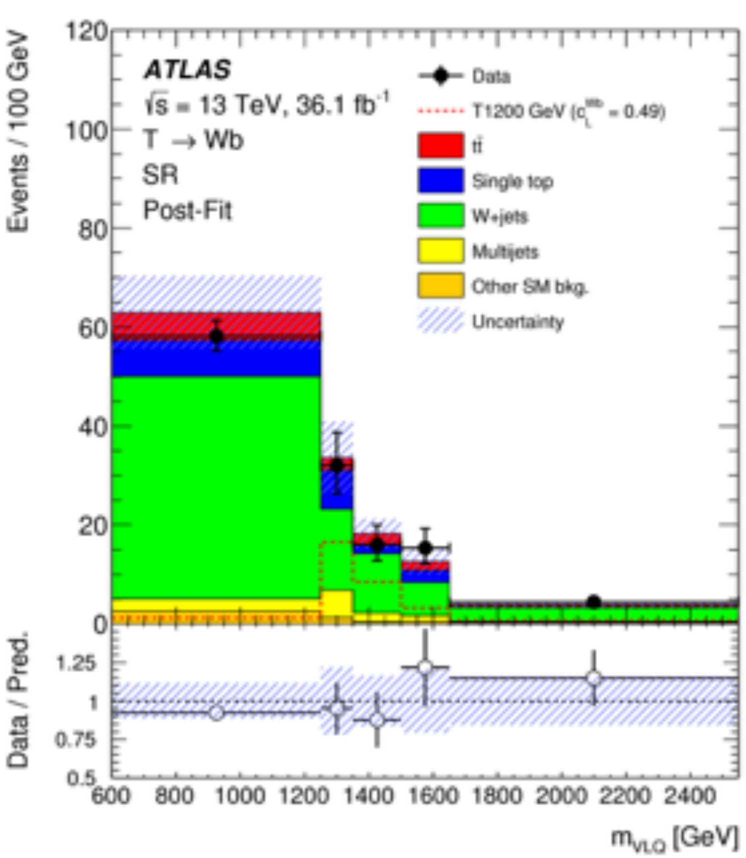
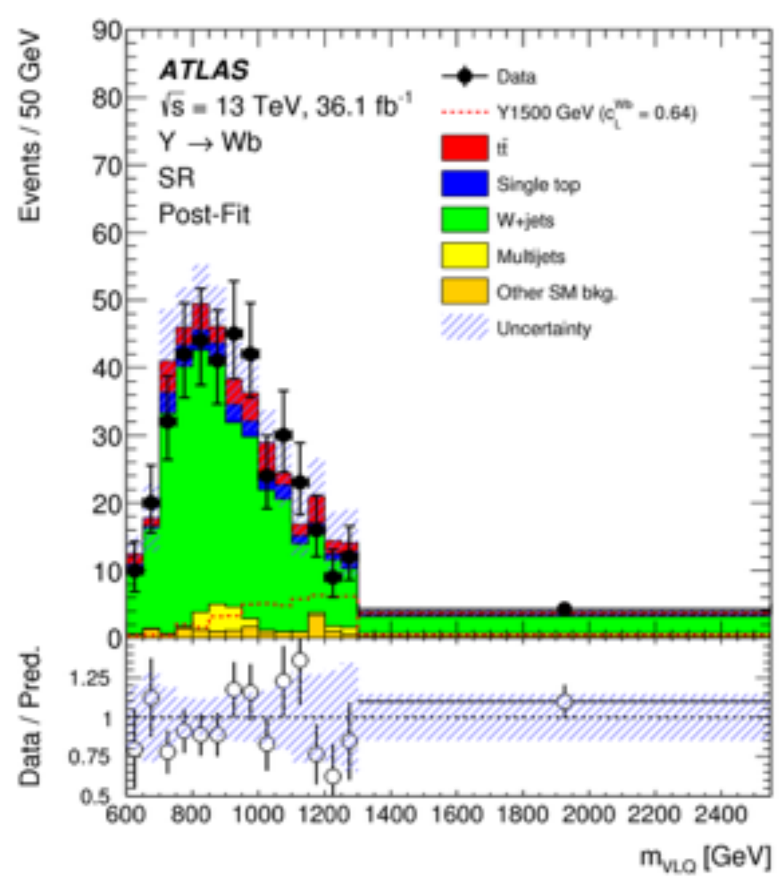
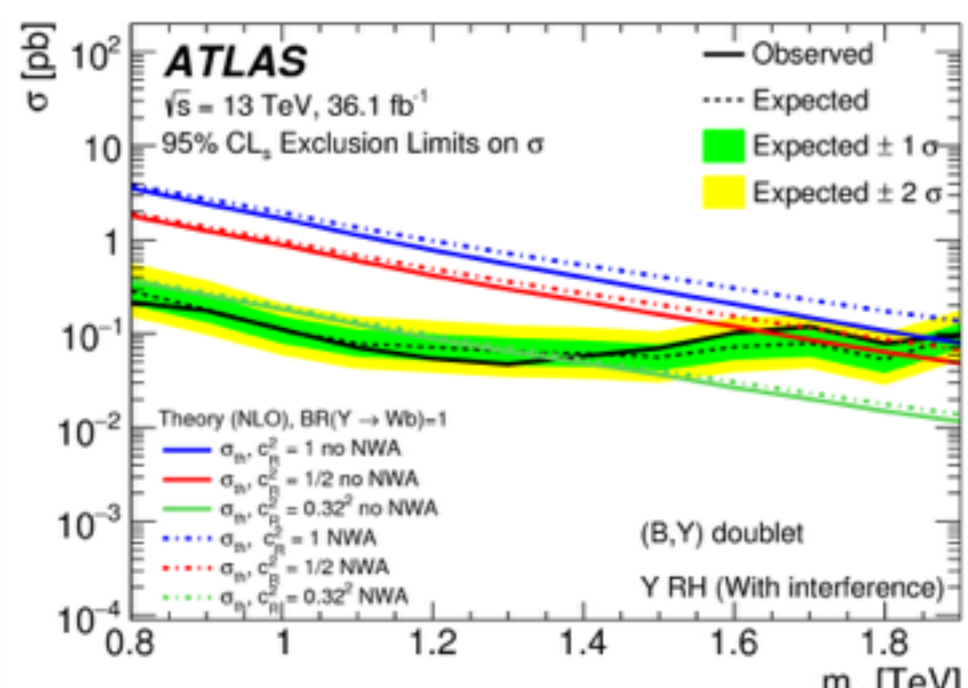
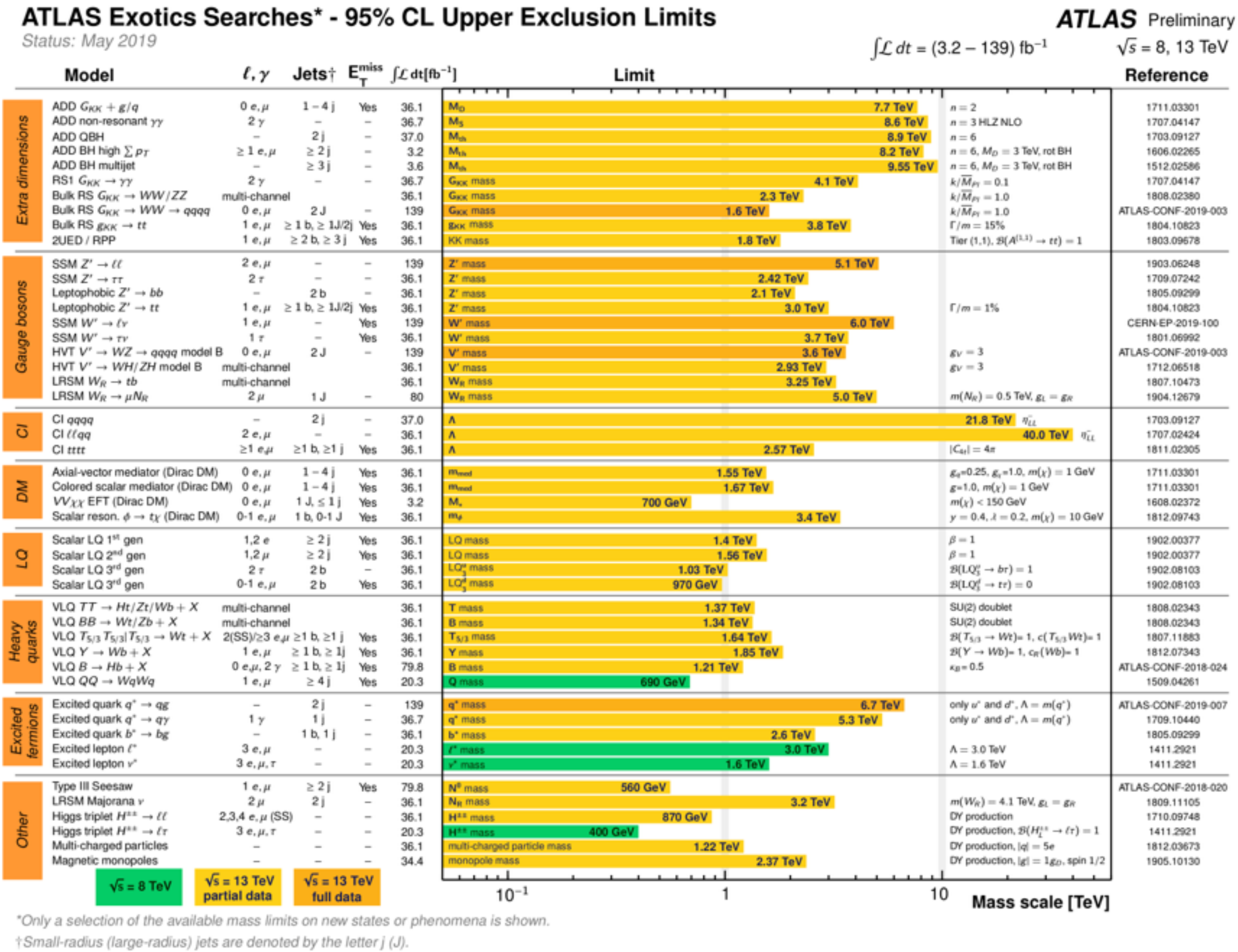
- Vector-like T (+2/3) quarks can belong to any weak-isospin multiplet, while vector-like Y(-4/3) can not be singlets, only consider (B, Y) doublet or (T, B, Y) triplet in this analysis
- Singly production (strong interaction) probe the VLQ coupling with SM quarks as a function of VLQ mass
- Dominant backgrounds coming from: W+jets, Top, QCD, Z, multi-bosons



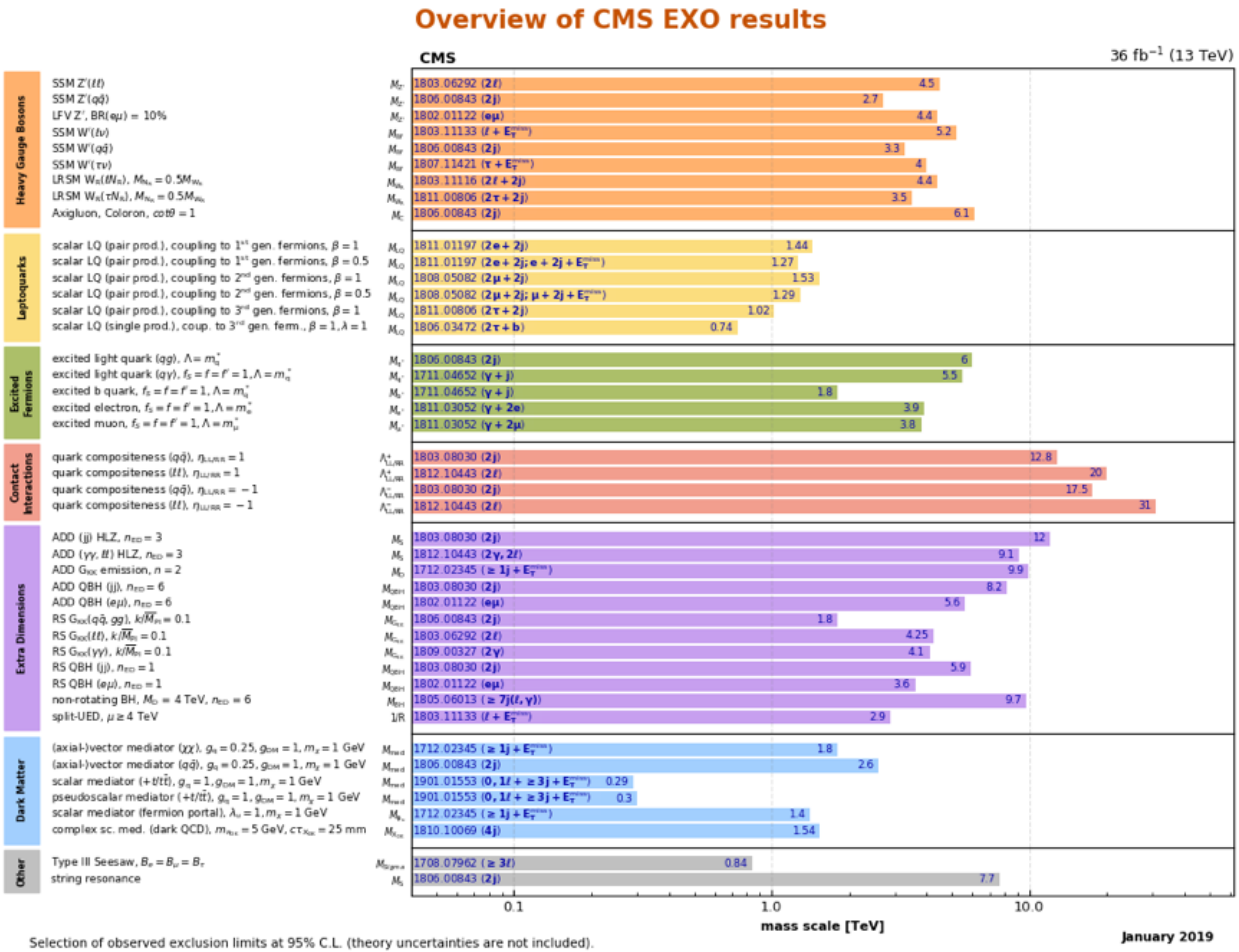




Limits for Exotics Searches Up to 2019 May



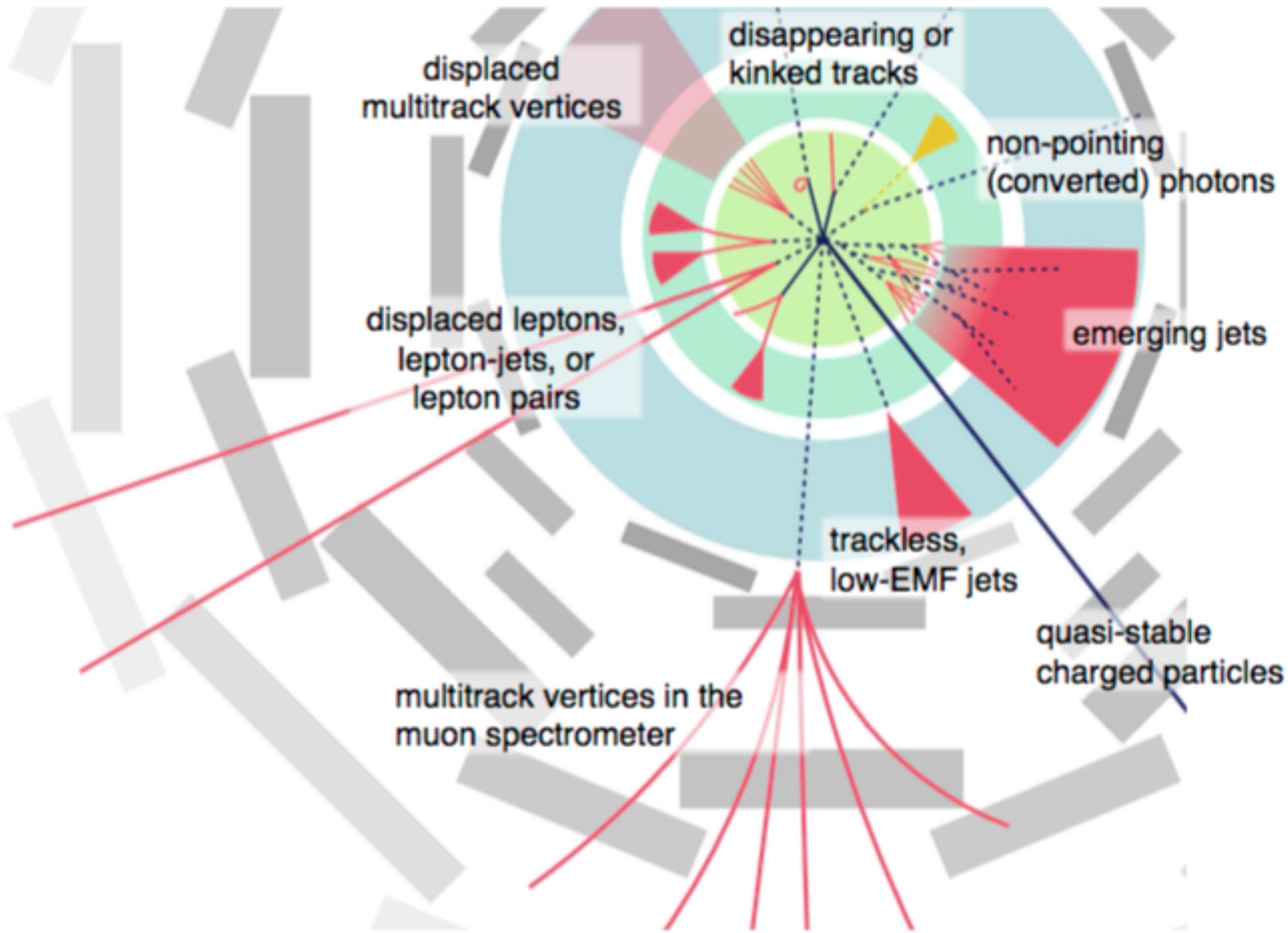
Limits for Exotics Searches based on 2016 Data



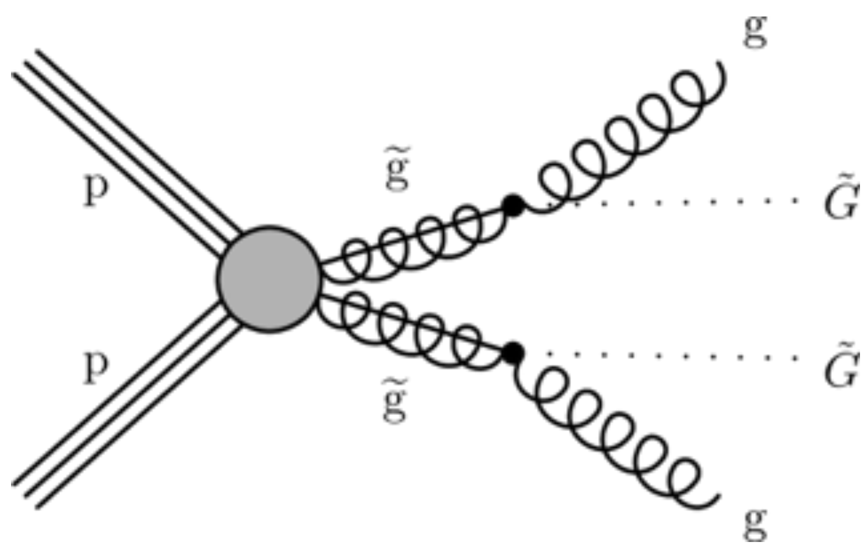
Long-lived Particle Search

Long-Lived Particles

- BSM particles may have lifetime that are long compared to SM particles, referred as Long-Lived particles (LLP), will decay far from interaction point.
- Search for LLP requires for customised techniques to identify displaced vertices.

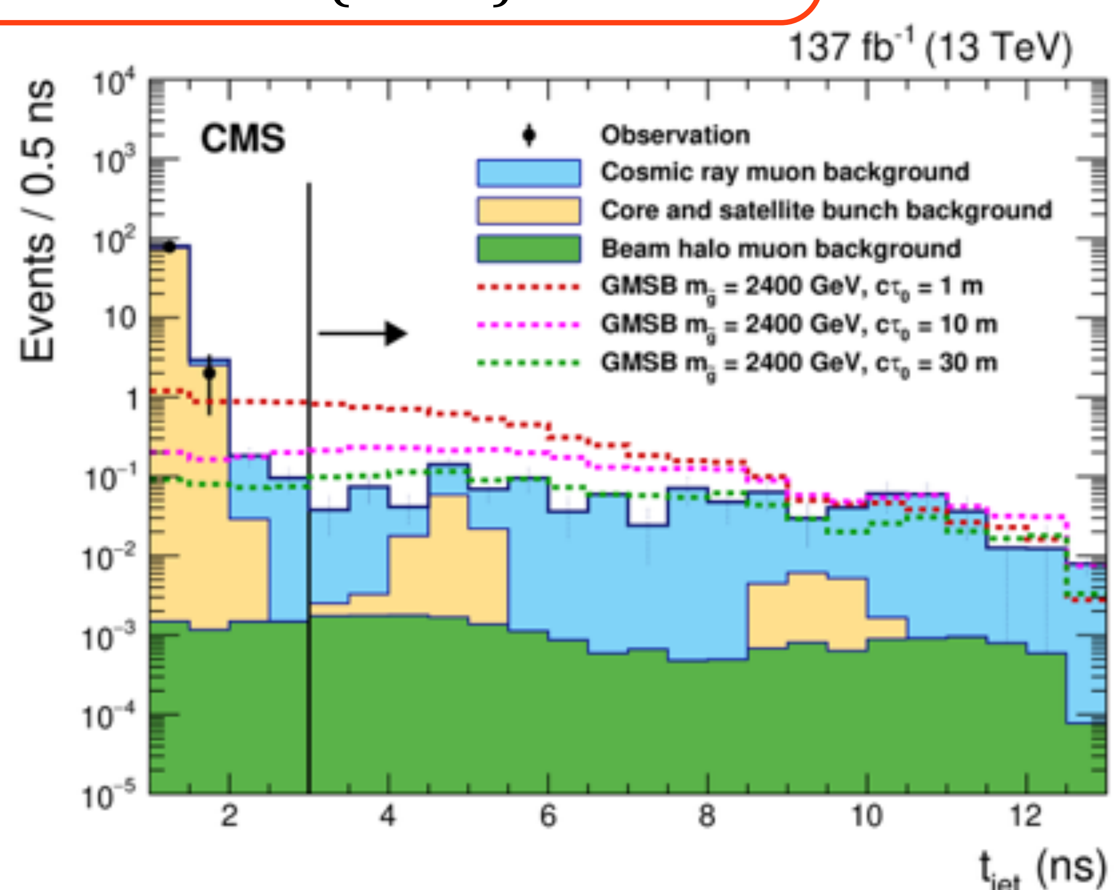


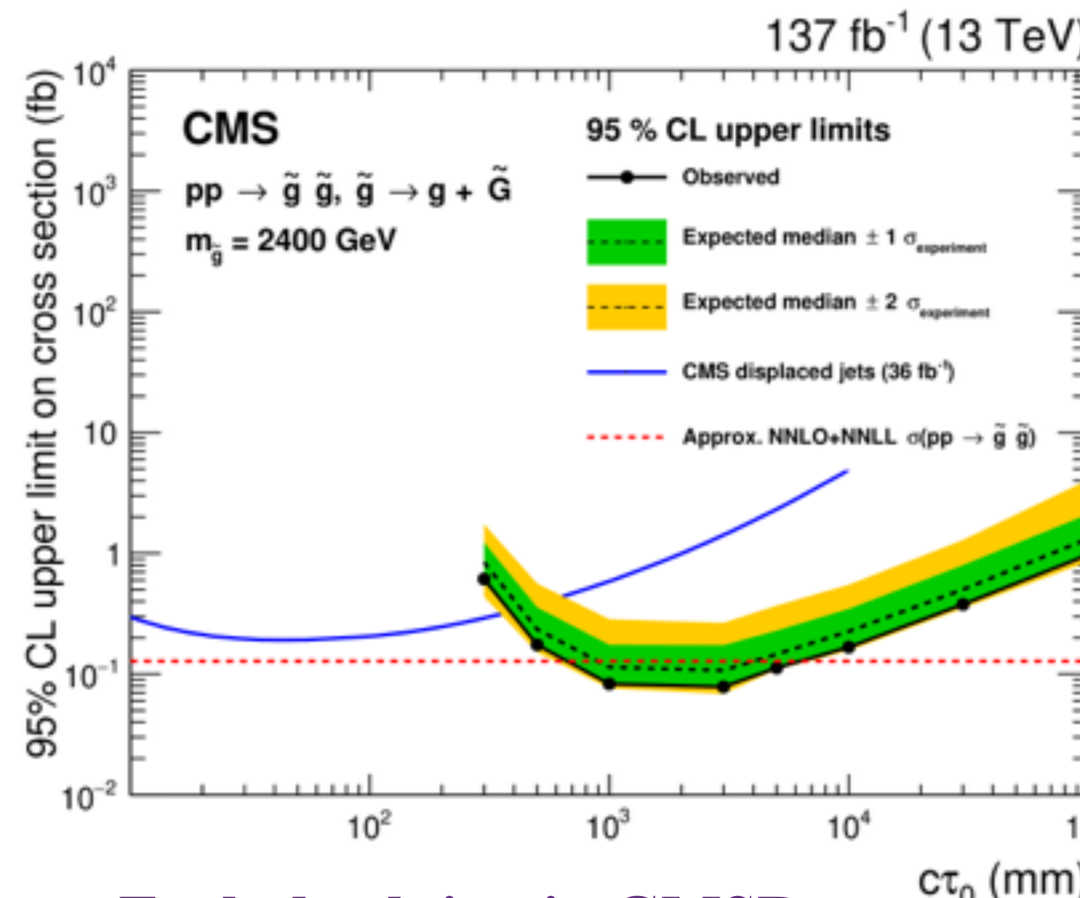
Displaced Jet + MET



- Several models can predict such signature: Gauge-mediated SUSY breaking (GMSB), split and stealth SUSY, hidden valley models
- The first time to use timing capability of ECAL (in CMS) to identify the displaced jet
    - SR: 3ns < t_{jet} < 20ns

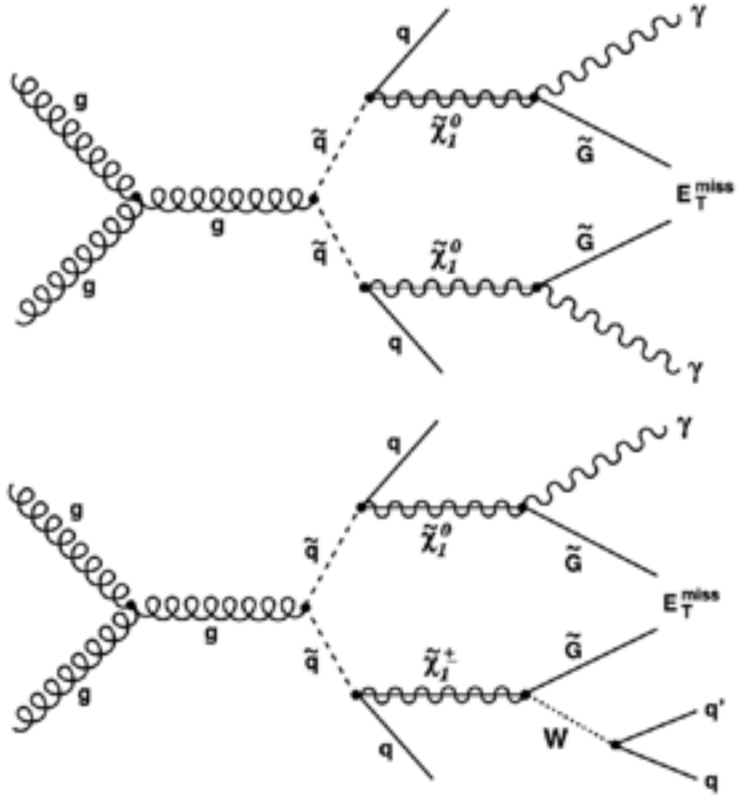
Phys. Lett. B 797 (2019) 134876





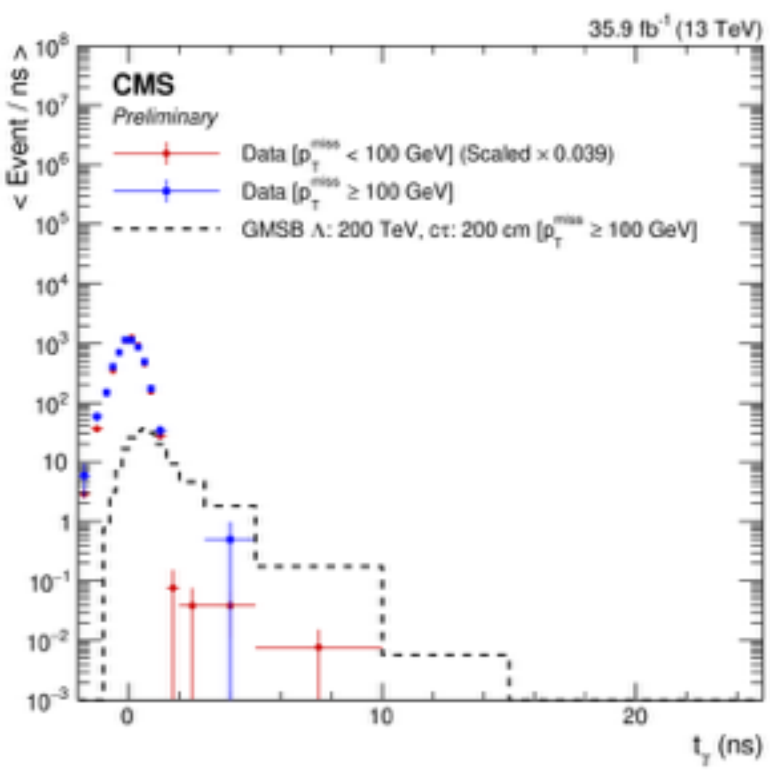
No events observed in SR: 3ns < t_{jet} < 20ns. Exclude gluino in GMSB with mass of 2.1 TeV, 2.5 TeV and 1.9 TeV for cτ of 0.3m, 1m and 100m respectively.

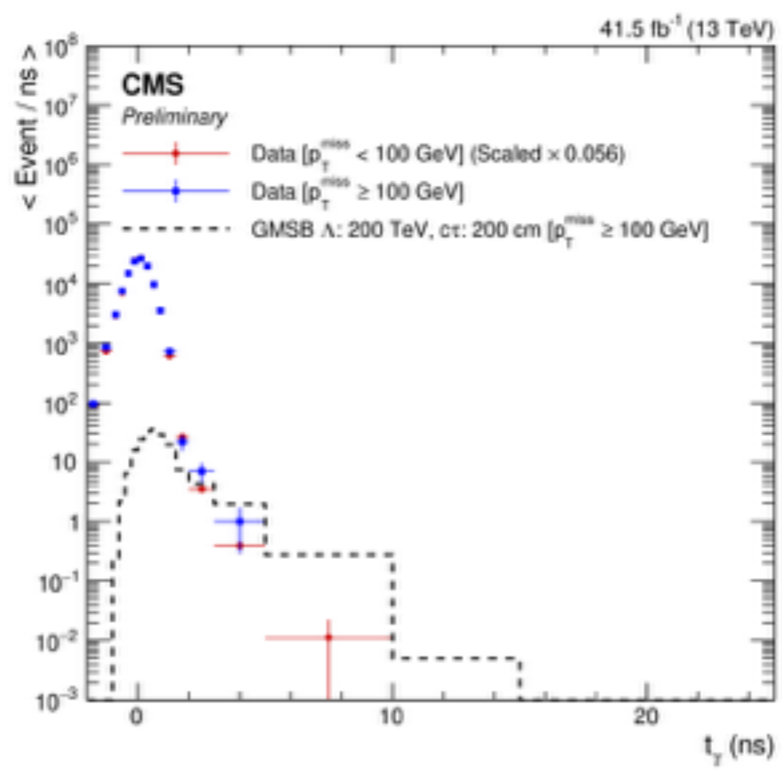
Displaced Photon

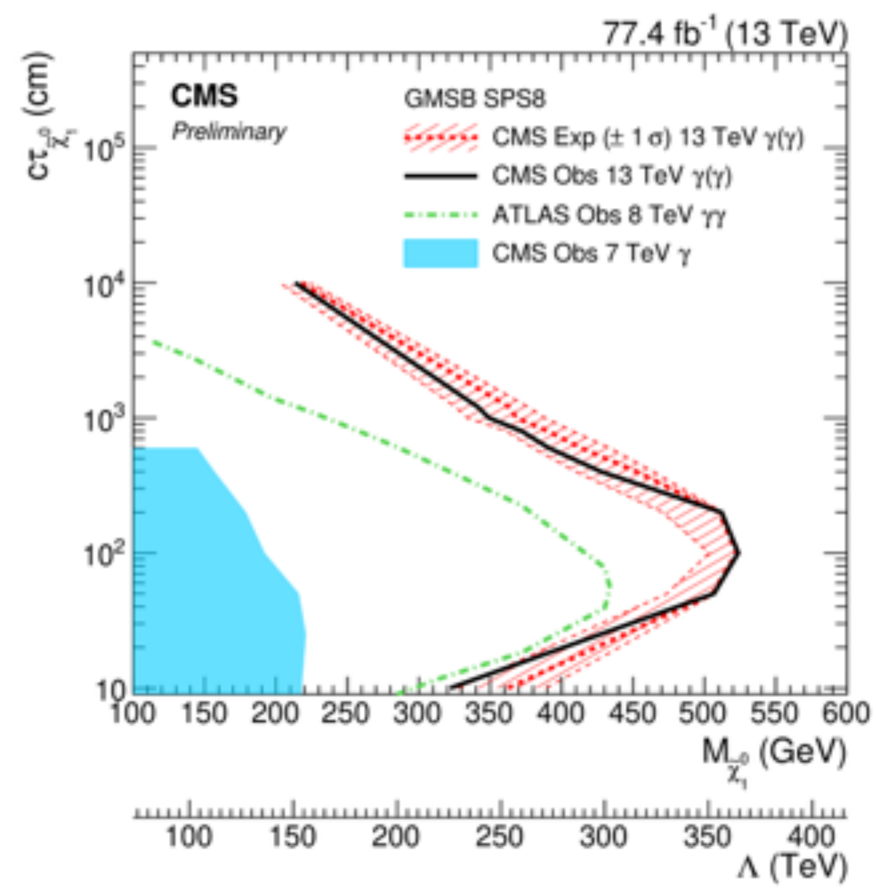


- Also test on benchmark model (GMSB)
- Requiring one or two photon with displaced vertex and three or more jets in the events.
- diphoton trigger for 2016 data, dedicated single photon trigger (designed for displaced photons) used in 2017 data.

CMS-PAS-EXO-19-005



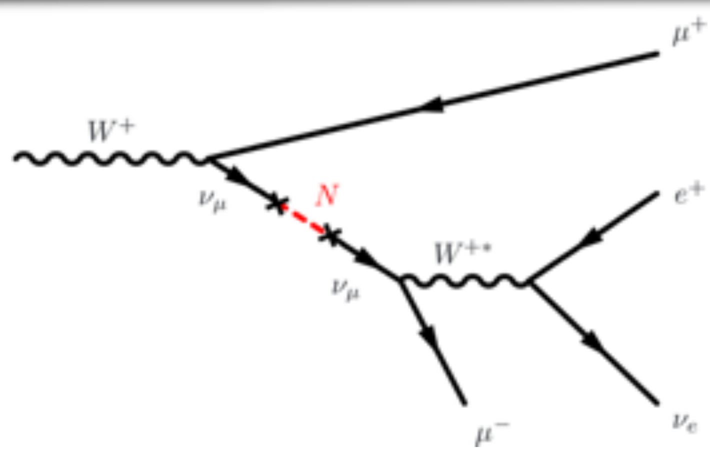




No sign observed for displaced Photon.

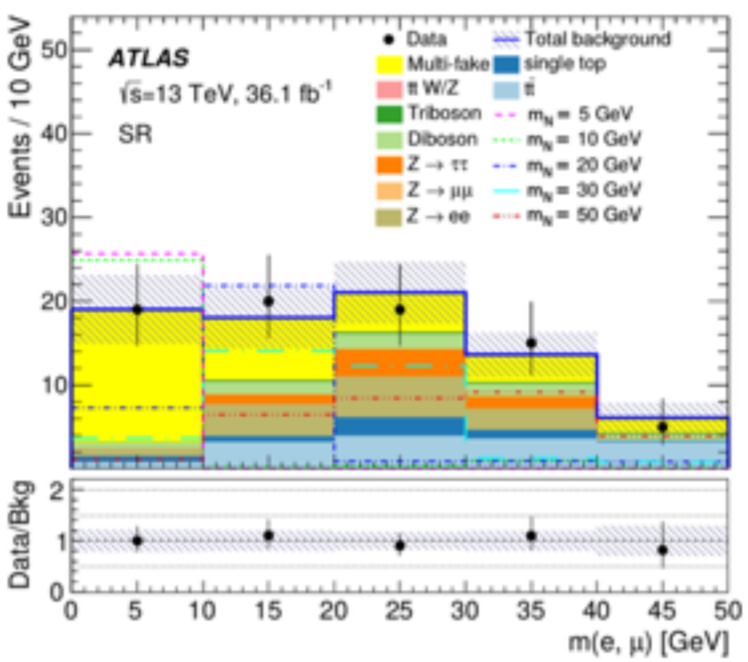
Significantly extend the limits in the 2D plane of cτ vs mass of neutralino.

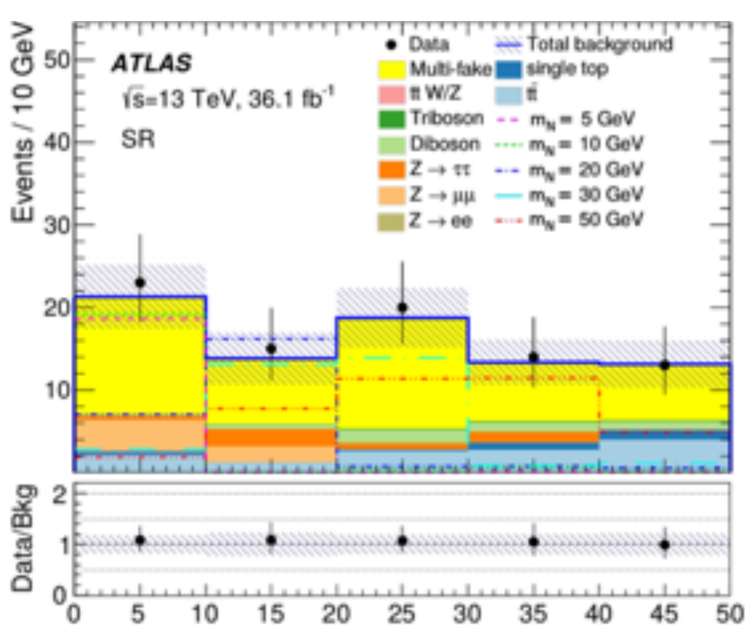
Search for Heavy Neutral Lepton

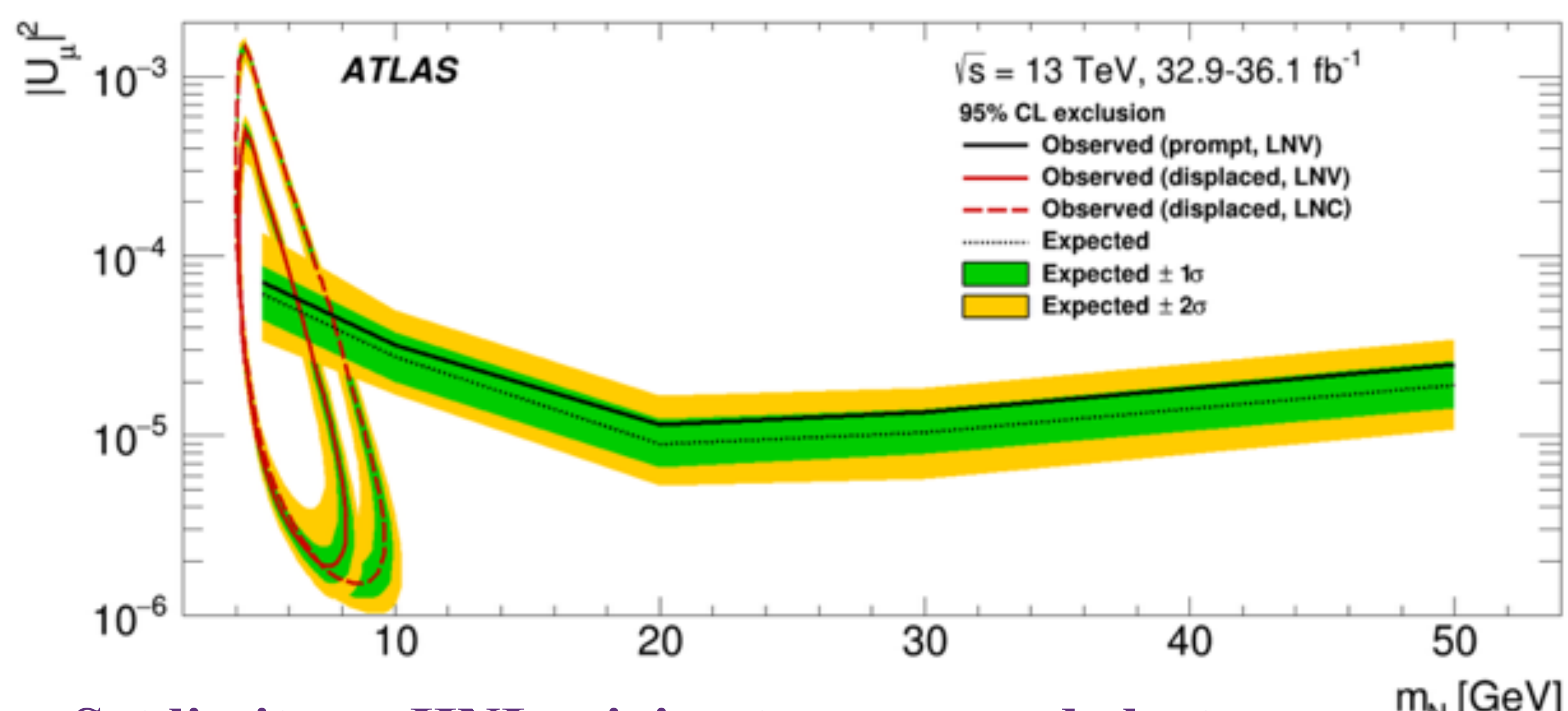


- **Heavy neutrino: can explain neutrino mass, matter-antimatter asymmetry, DM**
- **Search with both prompt and displaced signatures**
- **Signals include: $e^\pm e^\mp \mu^\pm$ or $\mu^\pm \mu^\mp e^\pm$ with small MET**
- **First displaced search featured with a prompt muon accompanies by a displaced vertex from two OS leptons**

arXiv:1905.09787

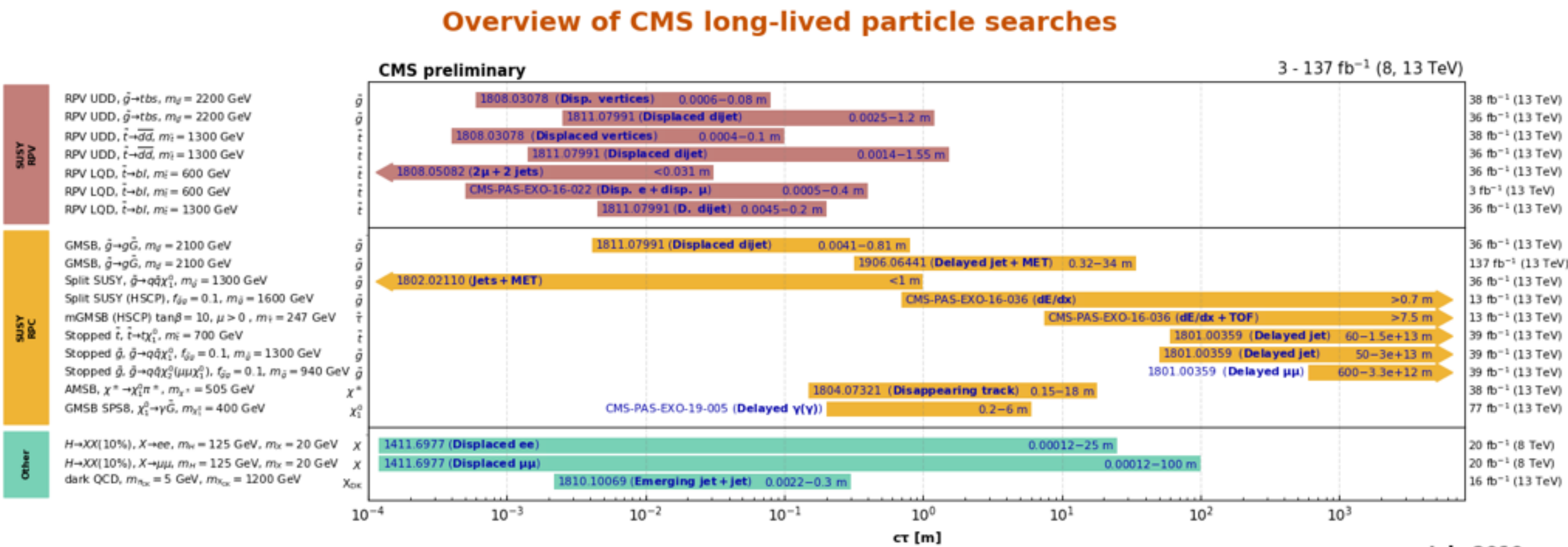






Set limits on HNL mixing to muon and electron neutrinos for HNL masses in the range 4.5−50 GeV.

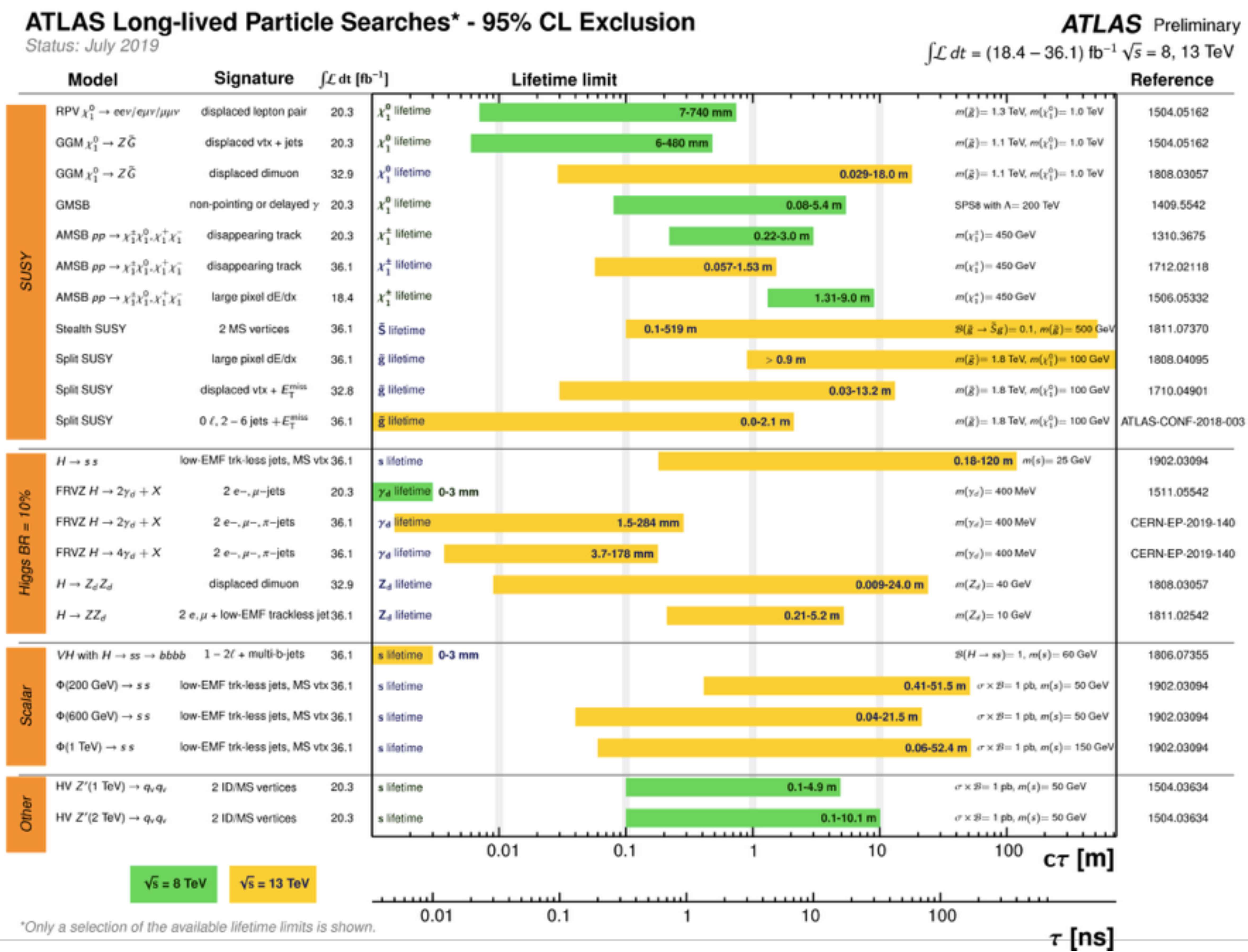
Limits for Long-Lived Particles



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

July 2019

Limits for Long-Lived Particles



Conclusion

- **Very Active field in the Exotics or other BSM searches**
  - probing various models beyond SM
  - developing new techniques to improve analysis sensitivity
  - combination of various channels

- **Early analyses with full Run 2 data performed**
  - dilepton, dijet, lepton + neutrino, displaced jet + MET …
  - No sign for new physics found yet!

- **Lots of analyses are on-going, stay-tuned for more exciting results!**
- **Surprise(s) may be hidden somewhere!**

- backup